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MICROPHOTOGRAPHY

Photography at Extreme Resolution

3

MICROPHOTOGRAPHY;

Photography at Extreme Resolution //

BY

G. W. W. STEVENS

Ph.D., F.R.P.S.

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5a
5b NEW YORK //
JOHN WILEY // & SONS INC.
440 Fourth Avenue
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1957 //

First Published 1957

PRINTED IN GREAT BRITAIN
BY BUTLER AND TANNER LIMITED, FROME AND LONDON

939090

PREFACE

THE FIRST really minute photographic images were made more than one hundred years ago. In 1839, within a few months of the importation of the Daguerreotype process from France, J. B. Dancer of Manchester tried to use it to record greatly reduced images. Similarly, within a few months of Scott Archer's invention of the Wet-Collodion process in 1852, Dancer reversed the optical train of a microscope to produce truly microscopic images. Several other experimenters (probably working independently) soon followed Dancer, and it seems probable that this activity may, at that time, have appeared to be a natural extension of existing photographic operations.

The work of Dancer and other pioneers has now been largely forgotten, and most photographers are to-day quite unaware of the possibilities revealed by their work. This has been reflected in the reactions, ranging from amazement to incredulity, which I have elicited when demonstrating how much information can be compressed into a small area on emulsions commercially available to-day. The limited spread of information on this subject is due to the fact that the available literature is scattered amongst original papers, whose technical content has never been collected together. A further hindrance is that the apparatus and working methods have never been described in sufficient detail, to permit photographers to feel that they could get satisfactory results without extensive preliminary experiments.

In the present volume I have collected those parts of the published information which seemed most important for the practice and application of microphotography. This has been supplemented by observations (many of them not previously published) from my own experiments in this field. My other main aim has been to describe the principles underlying sound microphotographic practice, so that readers may begin their own work with some understanding of what they are trying to do, and why. On the other hand, this book makes no claim to being an exhaustive treatise of the subject, and there are a number of admirable papers which I have not mentioned, since their content was not essential to my main theme. For this and other reasons I have no doubt that the subject-matter of Chapters 11 (Graticules) and 12 (Document Microphotography) could each be expanded to fill a book as large as this.

Most of my knowledge of this subject has been gained during my employment in the Kodak Research Laboratories at Wealdstone, Harrow ; and I am indebted to Dr. C. E. K. Mees, F.R.S., for permission to publish this book. At all stages my work has been greatly assisted by the encouragement and help of my colleagues. To Mr. E. R. Davies, O.B.E. (Director of Research of Kodak Ltd.), I am grateful for much encouragement, and for the freedom to pursue my interest in this topic. Help in practical matters has been received from many, but particular mention should be made of Drs. R. W. Berriman and E. P. Davey who evolved the " Maximum Resolution " emulsion, of Mr. M. P. Blaber and Mr. C. H. Mitson who helped to construct my first distance pieces, of Mr. J. L. Houghton and Mr. E. W. H. Selwyn who advised on optical matters, and of Mr. (now Dr.) A. T. James and Mr. P. Brooks and Miss J. Little who assisted me during critical stages of my work. Dr. R. S. Schultze and his library staff have brought many useful references to my attention, and he and other colleagues have reviewed various chapters. Mr. T. L. J. Bentley has read the entire book, and made many constructive suggestions.

In spite of the circumstances in which it has been written, I wish to emphasize that *this book should in no way be regarded as a publication of the Kodak Company.* Microphotography is a highly specialized art, and opinions which are quite justified in this special field may not apply without qualification to ordinary photographic practice. It is probable that some of my opinions may seem unorthodox, and will not be accepted by my colleagues. In short the opinions described here are my own, and this book constitutes an attempt to present the facts as clearly as I can see them.

My thanks are due to Dr. E. Bovey (head of Photographic and Optical Processes Department, British Scientific Instrument Research Association) for the specially contributed account in Chapter 11 of the work of his department. The following sources of other useful material are gratefully acknowledged :

The Royal Society . . .	The text of the " Fair Dealing " declaration (Chapter 12).
The Journal of Instrument Technology and Mr. K. F. H. Murrell	Information on the design of scales (Chapter 11).
The Royal Photographic Society .	Permission to reproduce the material of Chapter 10.
The Controller of H.M. Stationery Office	Permission to publish extracts from B.I.O.S. Report 1552, and also Figures 50 and 65 and Table IV.
The British Journal of Radiology .	Permission to reproduce experiments on autoradiography (Chapter 13).
Professor L. C. Martin and Dr. B. K. Johnson and Messrs. Blackie and Son	Permission to reproduce Table III.

Material for the illustrations has been supplied by :

Mr. J. Carter (62) ; Mr. R. D. Geiser of Messrs. W. and L. E. Gurley (66) ; Mr. C. H. Green, Eastman Kodak Co. (74) ; Mr. E. W. Jackson and the *British Journal of Photography* (67) ; Professor L. C. Martin and Messrs. Blackie and Son (64) ; Dr. S. R. Pelc (76) ; The Microcard Foundation (2) ; Mr. K. Stuart Smith, Recordak Division, Kodak Ltd. (1 and 72) ; Miss J. Tabor (7, 57 and 77).

Finally, I am indebted to my wife and to Dr. P. J. Hillson and Mr. D. Spracklen for their help in correcting the proofs.

G. W. W. STEVENS.

Fairbank,
118, *Uxbridge Road, Harrow Weald.*

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LIST OF JOURNALS CITED

Journal	*Abbreviation*
American Documentation	*Am. Doc.*
Annalen der Physik	*Ann. d. Phys.*
Aslib Proceedings	*Aslib Proc.*
Atlantic Monthly	—
British Journal of Photography	*Brit. J. Phot.*
British Journal of Radiology	*Brit. J. Radiol.*
Bulletin de l'Institut International de Bibliographie	*Bul. Inst. Int. Bibl.*
Bulletin de la Société Française de Photographie	*Bul. Soc. Franç. Phot.*
Catalogue of Exhibition of Scientific Instruments : Physical Society (London)	*Cat. Exh. Sci. Inst. : Phys. Soc.*
Electronics	—
English and Amateur Mechanic	*Eng. Am. Mech.*
Handbook of Exhibition of Scientific Instruments : Physical Society (London)	*Handbook Exh. Sci. Inst. : Phys. Soc.*
Illustrated London News	*Ill. Lon. N.*
Industrial and Engineering Chemistry	*Ind. Eng. Chem.*
Instrument Maker	*Inst. Maker*
International Congress of Photography	*Int. Congress Phot.*
Isis	—
Journal of the American Chemical Society	*J. Am. Chem. Soc.*
Journal of Documentary Reproduction	*J. Doc. Repr.*
Journal of the Franklin Institute	*J. Frank. Inst.*
Journal of the Optical Society of America	*J. Opt. Soc. Am.*
Journal of the Photographic Society of America	*J. Phot. Soc. Am.*
Journal of Research : National Bureau of Standards	*J. Res. : Nat. Bur. Stand.*
Journal of the Royal Microscopical Society	*J. Roy. Micro. Soc.*
Journal of Scientific Instruments	*J. Sci. Inst.*
Journal of the Society of Motion Picture and Television Engineers	*J. Soc. Mot. Pic. Tel. Eng.*
Machinist	—
Microscopical Journal	*Micro. J.*
Microtecnic	—
Nature	—
Penrose Annual	*Penr. Ann.*
Philips Technical Review	*Philips Tech. Rev.*
Photographic Engineering	*Phot. Eng.*
Photographic Journal	*Phot. J.*
Physical Review	*Phys. Rev.*
Proceedings of the Annual Meeting of the National Microfilm Association	*Proc. Ann. M. Nat. Microfilm Assoc.*
Proceedings of the British Society for International Bibliography	*Proc. Brit. Soc. Int. Bibl.*
Proceedings of the Physical Society (London)	*Proc. Phys. Soc.*
Proceedings of the Royal Society	*Proc. Roy. Soc.*
Process Engraver's Monthly	*Proc. Eng. M.*

Journal	*Abbreviation*
Quarterly Journal of Microscopical Science	*Q. J. Micro. Sci.*
Reader's Digest	—
Review of Documentation	*Rev. Doc.*
Revue d'Optique	*Rev. Opt.*
Silliman's Journal	—
Technical Physics of the U.S.S.R.	*Tech. Phys. U.S.S.R.*
Times Review of Industry	*Times Rev. Ind.*
Transactions of the Illuminating Engineering Society (New York)	*T. Ill. Eng. Soc.*
Transactions of the Optical Society (London)	*T. Opt. Soc.*
Transactions of the Society of Instrument Technology	*T. Soc. Inst. Tech.*
Wiedemann's Annalen der Physik und Chemie	*Wied. Ann.*
Zeitschrift für Instrumentkunde	*Z. Inst. K.*
Zeitschrift für Vermessungswesen	*Z. Vermw.*
Zeitschrift für Wissenschaftliche Photographie	*Z. Wiss. Phot.*

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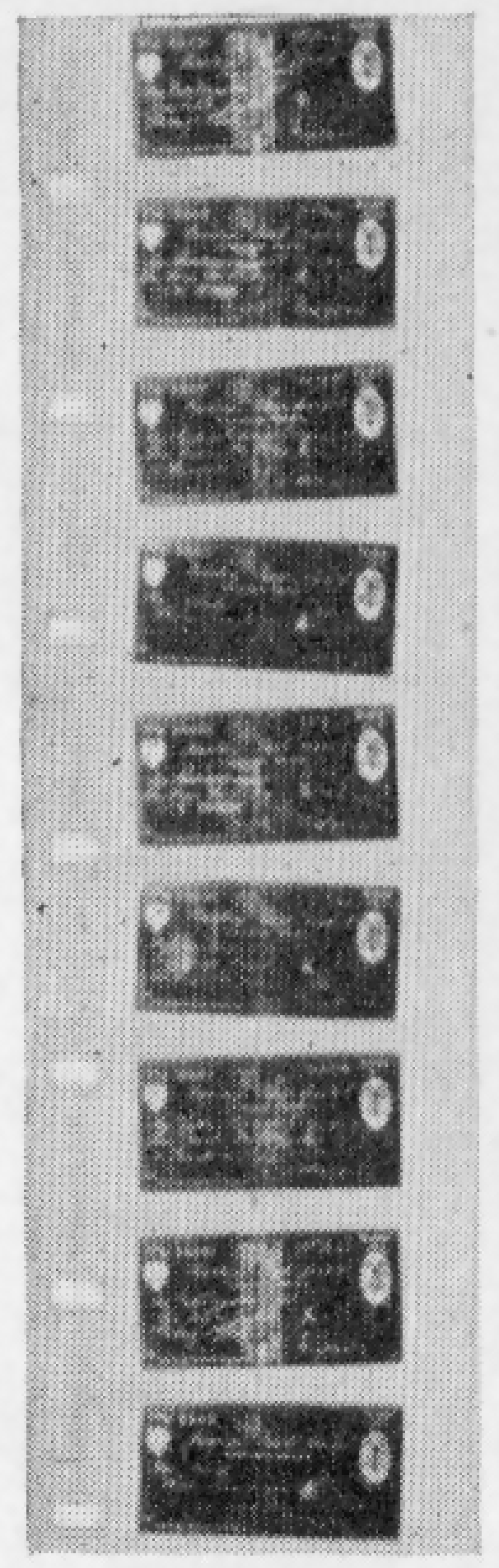
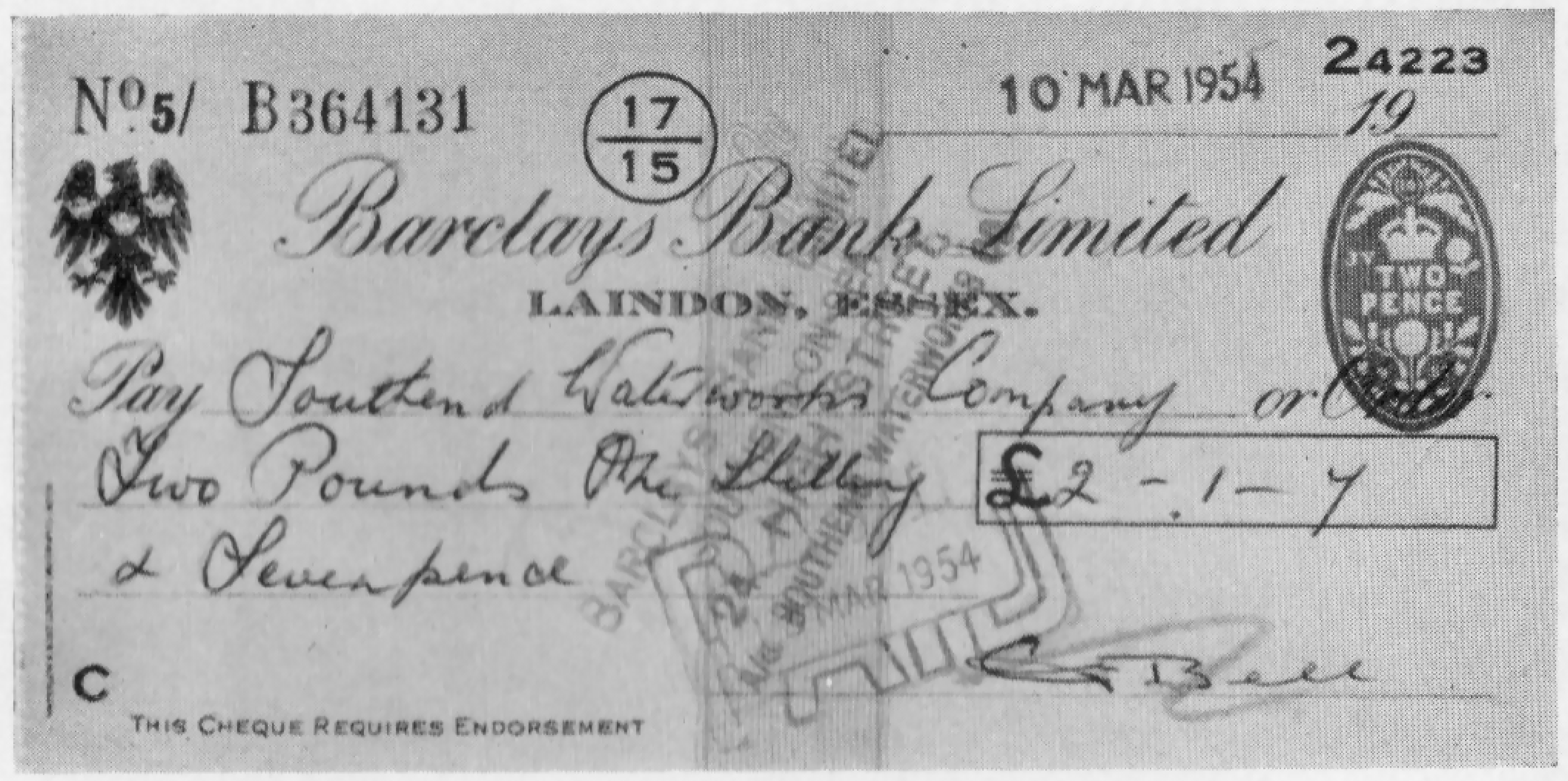


(*a*) 16-mm. film containing row of ×18 reduced negatives.

Original Cheque



No5/ B364131 17/15 10 MAR 1954 24223 19

Barclays Bank Limited

LAINDON, ESSEX.

Pay Southend Waterworks Company or Order

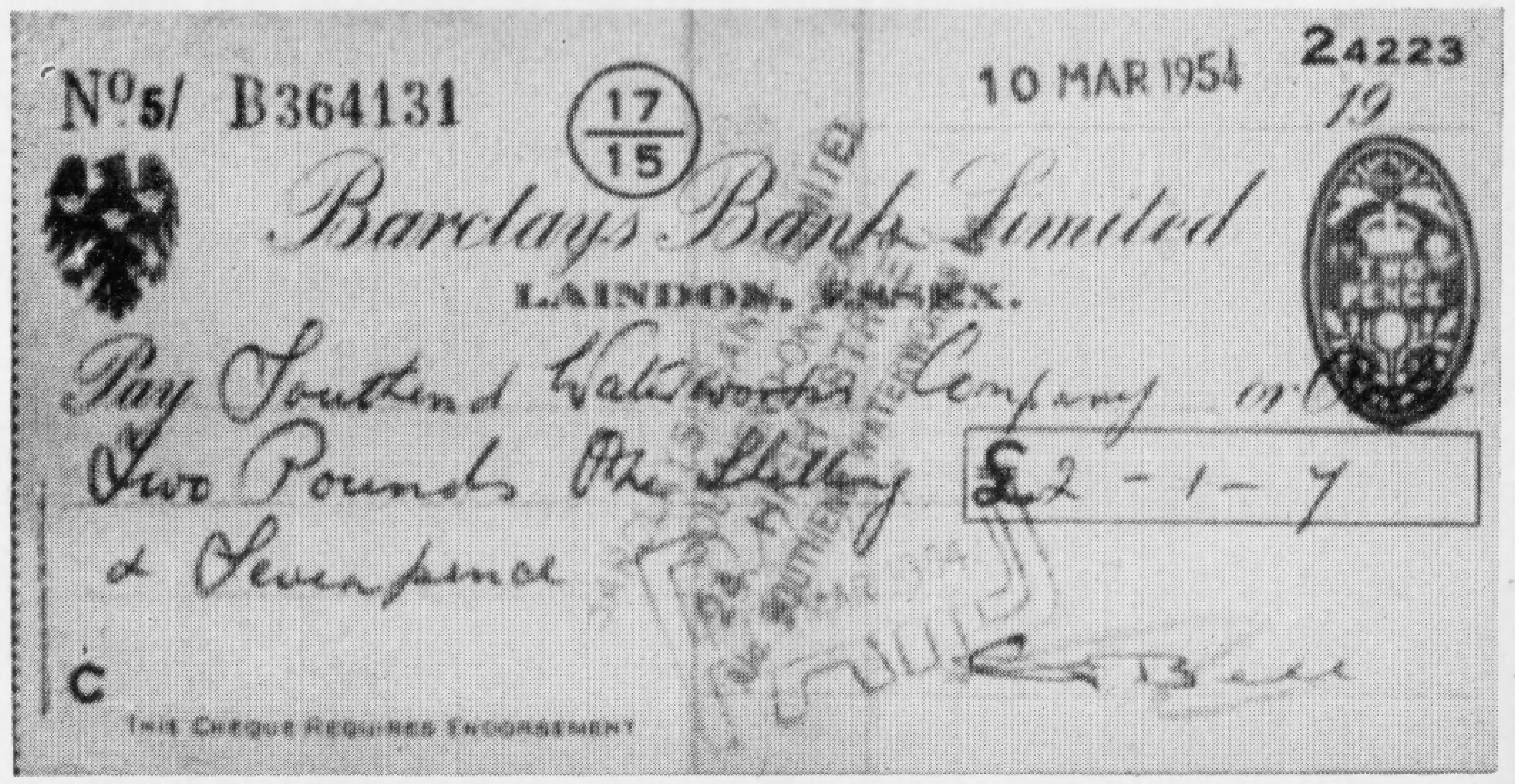
Two Pounds One Shilling £2-1-7

& Sevenpence

C

THIS CHEQUE REQUIRES ENDORSEMENT

Enlargement from Microfilm



No5/ B364131 17/15 10 MAR 1954 24223 19

Barclays Bank Limited

LAINDON, ESSEX.

Pay Southend Waterworks Company or Order

Two Pounds One Shilling £2-1-7

& Sevenpence

C

THIS CHEQUE REQUIRES ENDORSEMENT

(*b*) Comparison of an original cheque with an enlargement from the film shows that all significant details are reproduced.

FIG. 1. *Microphotography of Cheques.*

Courtesy of Mr. K. Stuart-Smith. Recordak Division, Kodak Ltd., London.

CHAPTER 1

The Study of Microphotography

The Scope of Microphotography

THIS BOOK describes the production and applications of *microphotographs*, that is, photographs which are reduced to a minute or even to a microscopic scale. Such photographs are widely used in certain commercial and scientific operations, and microphotography constitutes a little-known activity of real importance to our material civilization. The most extensive application is the reproduction of documents, and a very large number of cheques, invoices and other business papers are copied every day (*Figure* 1). By this means microphotography facilitates duplication and transport of records, saves filing space and provides an insurance against accidental loss or destruction of the original documents. The ease of transporting document microphotographs was utilized in the " Airgraph " and " V-mail " postal services operated by the Allies during the Second World War. Letters for overseas destinations were written on special forms and were reduced on microfilm which was sent to the country of destination. They were then enlarged to legible size by means of automatic machines, and the enlargements were distributed by the normal postal services (see *Figure* 72). Microphotographs have also been used in the transmission of secret information for espionage. In one form copies of documents were reduced to the size of a full stop, and were implanted in the surface of an otherwise innocent document (Chapter 12, page 242).

Document microphotography is also important to the scholar, since it enables him to secure for private study copies of documents which could formerly only be consulted in the (sometimes distant) libraries housing the originals. The value of this development can be seen from two examples. The Royal Society of Medicine in London operates a comprehensive and world-wide information and loan service for its members, and has collected microfilms of original papers published all over the world. From this collection doctors, specialists or research workers can readily obtain copies pertaining to their own fields of study. An even larger service is being offered by the Microcard Foundation of Middletown, U.S.A., which was specifically established for the purpose of organizing the distribution of microphotographic copies of expensive or inaccessible books. The copies used for this purpose take the form of standard 5 × 3 in. (12·5 × 7·5 cm.) filing cards, bearing microphotographic reproductions of some fifty pages of the original text (*Figure* 2). Thus a weighty volume of 900 pages can be compressed into 18 cards, and the cost of these reproductions is only a fraction of that of the original books. This service permits scholars to acquire texts hitherto beyond their reach (or purses !), and to collect the basic literature of their subject in a few boxes of filing cards.

The dissemination of information is only one of the aids which microphotography offers the scientist (Chapters 12 and 13). Microphotographic processes are used for making fine graduated scales (graticules),* including eyepiece scales for microscopes and other scientific and military instruments, stage micrometers for measuring the magnification of microscopes, and profile graticules for the optical inspection of the form of mechanical components such as screw threads. The latter are used in precision engineering for determining whether components of critical importance comply satisfactorily with their computed form. The introduction of photographic methods for reproducing instrument scales has had an important effect on the design of such instruments as theodolites, enabling unimpaired accuracy to be obtained with instruments which are more portable and quicker to use (Chapter 11). Microphotography is also likely to influence such operations as the accurate measurement of length. Hitherto this has frequently been done with the aid of a specially cut micrometer thread : the distance being determined by the number of turns (and fraction of a turn) needed to move the line of sight of a telescope from one end of an object to the other. Methods are now being developed which permit the thread to be replaced by an extremely accurate photographic scale of the required length, subdivided into sufficiently small graduations to permit the length of the object to be read directly from the scale.

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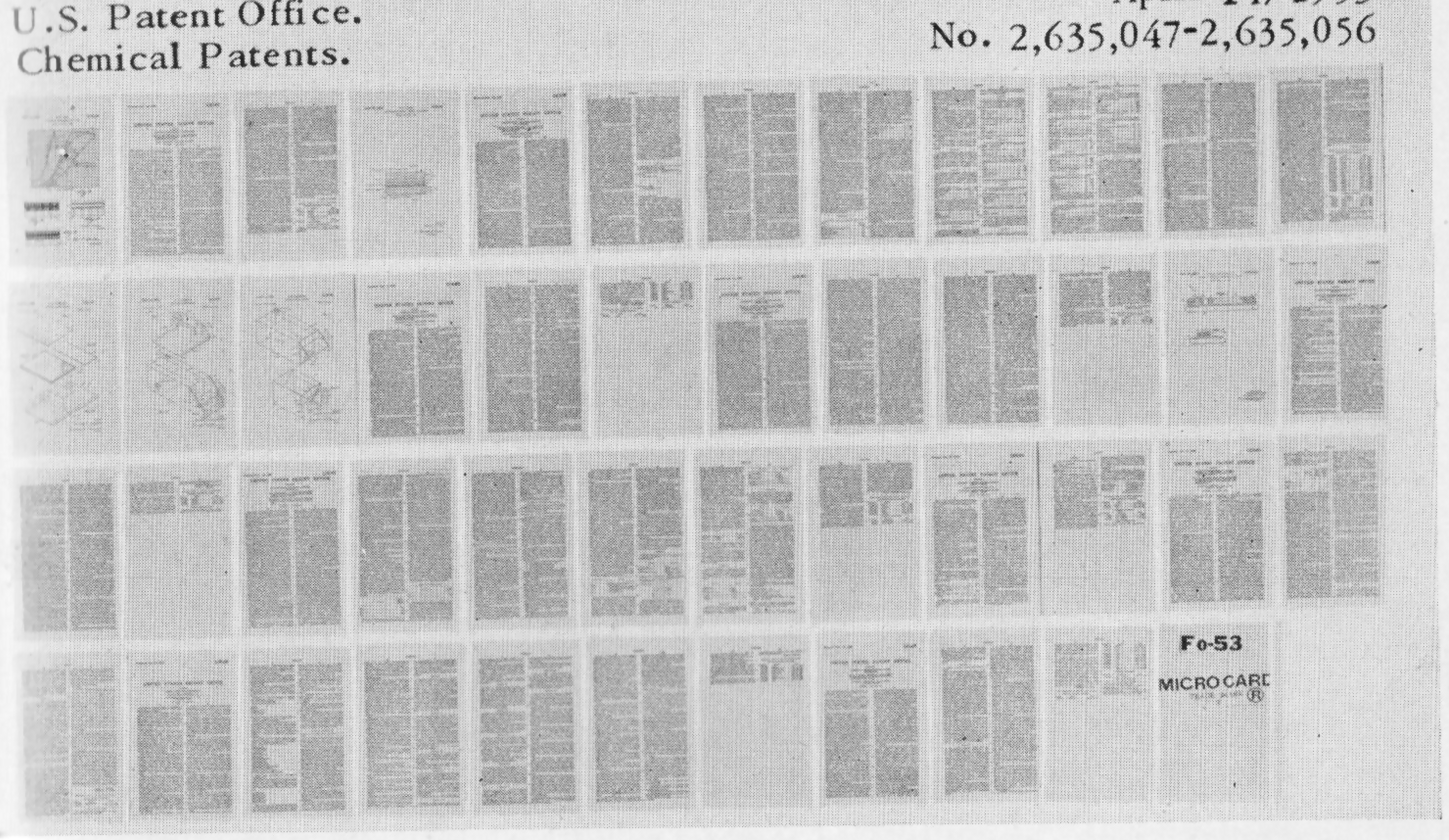
* Throughout this book, American readers should note that *graticule* and *reticle* are considered to be synonymous.

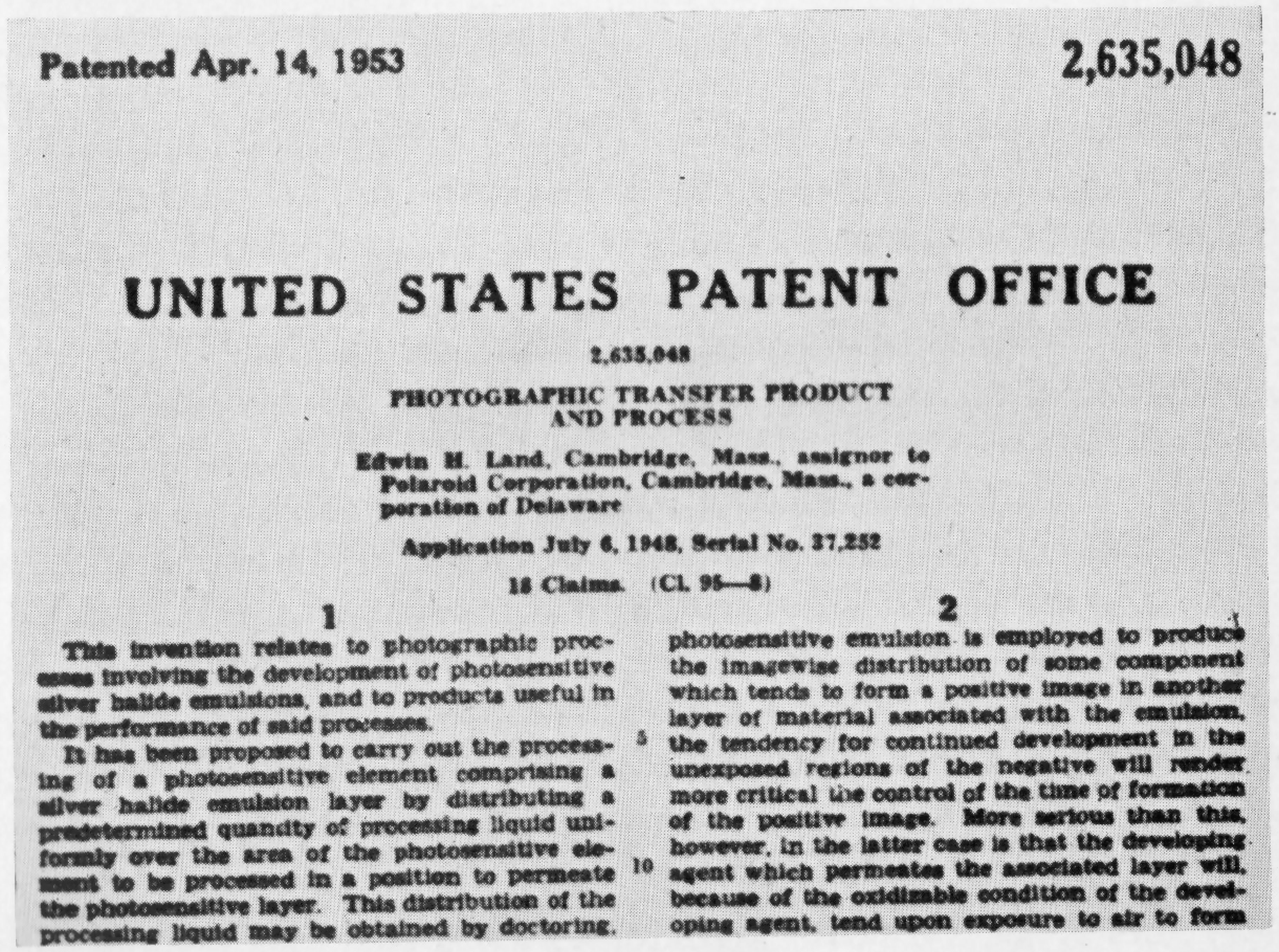


U.S. Patent Office.
Chemical Patents.

April 14, 1953
No. 2,635,047-2,635,056

Fo-53
MICROCARD

(*a*) The 5 × 3 in. (12·5 × 7·5 cm.) card shows easily legible bibliographical details, and reduced images of 46 pages. This card contains the complete text of 10 United States patent specifications.



Patented Apr. 14, 1953

2,635,048

UNITED STATES PATENT OFFICE

2,635,048

PHOTOGRAPHIC TRANSFER PRODUCT
AND PROCESS

Edwin H. Land, Cambridge, Mass., assignor to
Polaroid Corporation, Cambridge, Mass., a corporation of Delaware

Application July 6, 1948, Serial No. 37,252

18 Claims. (Cl. 95—8)

1

This invention relates to photographic processes involving the development of photosensitive silver halide emulsions, and to products useful in the performance of said processes.

It has been proposed to carry out the processing of a photosensitive element comprising a silver halide emulsion layer by distributing a predetermined quancity of processing liquid uniformly over the area of the photosensitive element to be processed in a position to permeate the photosensitive layer. This distribution of the processing liquid may be obtained by doctoring.

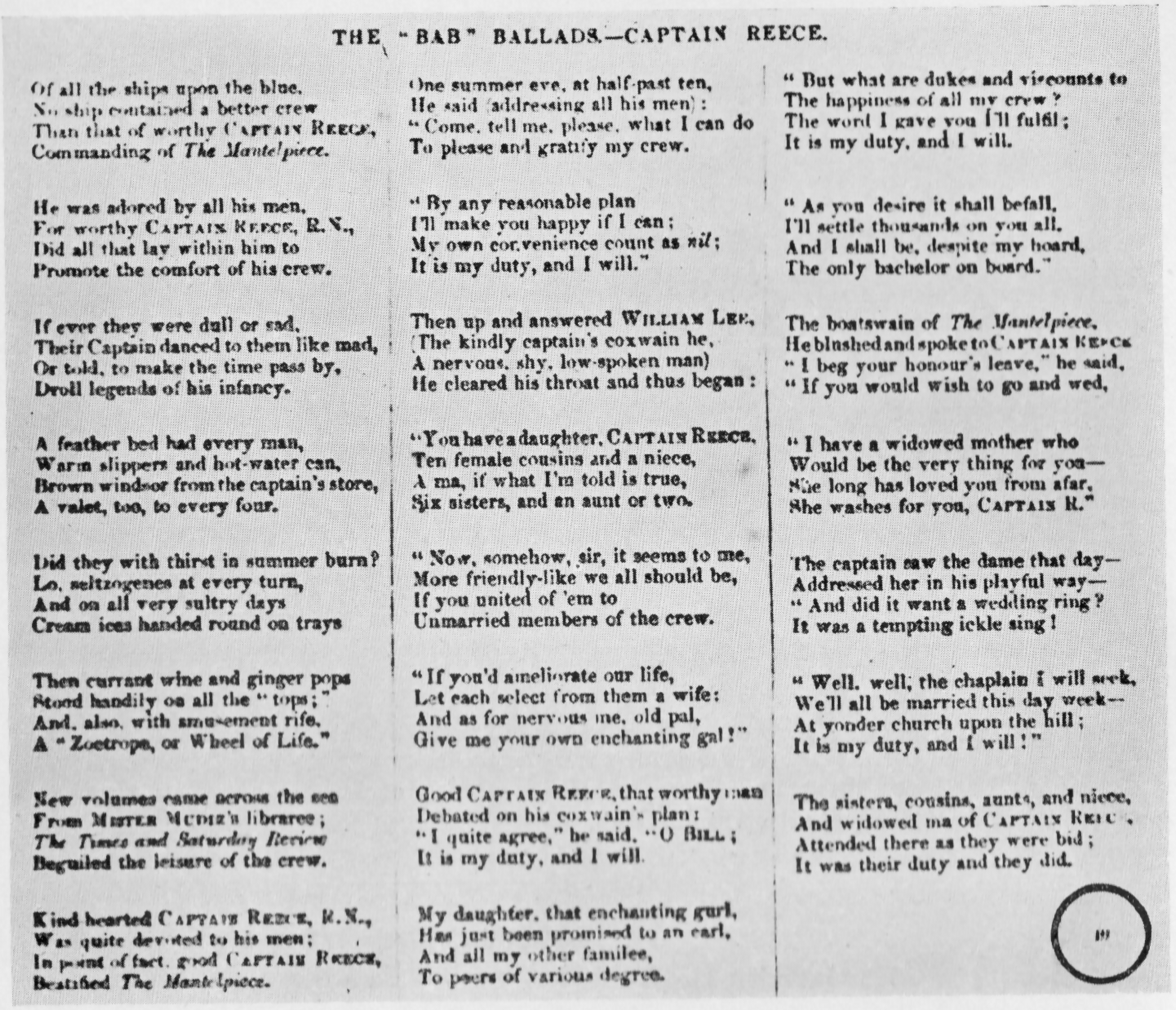
2

photosensitive emulsion is employed to produce the imagewise distribution of some component which tends to form a positive image in another layer of material associated with the emulsion, the tendency for continued development in the unexposed regions of the negative will render more critical the control of the time of formation of the positive image. More serious than this, however, in the latter case is that the developing agent which permeates the associated layer will, because of the oxidizable condition of the developing agent, tend upon exposure to air to form

(*b*) Photomicrograph (×12) of part of one of the images.

FIG. 2. "*Microcard*" *used for the Re-publication of Scholarly Information.*

Original by courtesy of The Microcard Foundation.



THE "BAB" BALLADS.—CAPTAIN REECE.

Of all the ships upon the blue,
No ship contained a better crew
Than that of worthy Captain Reece,
Commanding of *The Mantelpiece*.

He was adored by all his men,
For worthy Captain Reece, R.N.,
Did all that lay within him to
Promote the comfort of his crew.

If ever they were dull or sad,
Their Captain danced to them like mad,
Or told, to make the time pass by,
Droll legends of his infancy.

A feather bed had every man,
Warm slippers and hot-water can,
Brown windsor from the captain's store,
A valet, too, to every four.

Did they with thirst in summer burn?
Lo, seltzogenes at every turn,
And on all very sultry days
Cream ices handed round on trays

Then currant wine and ginger pops
Stood handily on all the "tops;"
And, also, with amusement rife,
A "Zoetrope, or Wheel of Life."

New volumes came across the sea
From Mister Mudie's libraree;
The Times and Saturday Review
Beguiled the leisure of the crew.

Kind-hearted Captain Reece, R.N.,
Was quite devoted to his men;
In point of fact, good Captain Reece,
Beatified *The Mantelpiece*.

One summer eve, at half-past ten,
He said (addressing all his men):
"Come, tell me, please, what I can do
To please and gratify my crew.

"By any reasonable plan
I'll make you happy if I can;
My own convenience count as *nil*;
It is my duty, and I will."

Then up and answered William Lee,
(The kindly captain's coxwain he,
A nervous, shy, low-spoken man)
He cleared his throat and thus began:

"You have a daughter, Captain Reece,
Ten female cousins and a niece,
A ma, if what I'm told is true,
Six sisters, and an aunt or two.

"Now, somehow, sir, it seems to me,
More friendly-like we all should be,
If you united of 'em to
Unmarried members of the crew.

"If you'd ameliorate our life,
Let each select from them a wife:
And as for nervous me, old pal,
Give me your own enchanting gal!"

Good Captain Reece, that worthy man
Debated on his coxwain's plan:
"I quite agree," he said, "O Bill;
It is my duty, and I will.

My daughter, that enchanting gurl,
Has just been promised to an earl,
And all my other familee,
To peers of various degree.

"But what are dukes and viscounts to
The happiness of all my crew?
The word I gave you I'll fulfil;
It is my duty, and I will.

"As you desire it shall befall,
I'll settle thousands on you all,
And I shall be, despite my hoard,
The only bachelor on board."

The boatswain of *The Mantelpiece*,
He blushed and spoke to Captain Reece
"I beg your honour's leave," he said,
"If you would wish to go and wed,

"I have a widowed mother who
Would be the very thing for you—
She long has loved you from afar,
She washes for you, Captain R."

The captain saw the dame that day—
Addressed her in his playful way—
"And did it want a wedding ring?
It was a tempting ickle sing!

"Well, well, the chaplain I will seek,
We'll all be married this day week—
At yonder church upon the hill;
It is my duty, and I will!"

The sisters, cousins, aunts, and niece,
And widowed ma of Captain Reece,
Attended there as they were bid;
It was their duty and they did.

FIG. 3. *Early Microphotograph produced by J. B. Dancer.*

Ninety-year-old microphotograph, sold at price of one shilling. Inset, size of original image.

From the Kodak Museum, Harrow.

[*Facing p. 3.*

These scientific applications are mainly convenient devices for reducing the effort needed to perform frequently repeated tasks, but the tasks themselves could still be accomplished without microphotography by less convenient methods. In some scientific investigations, however, microphotography plays an essential part in the experimental technique, so that the experiments could not be performed at all without its aid. One example is the use of a microphotographic emulsion for demonstrating that light normally reflected from a mirror forms a system of stationary waves, and another is the use of a fine grid pattern for demonstrating the minute lateral shifts of the emulsion occurring during the glazing of photographic prints (*Figure* 83).

The value of these various applications provides sufficient justification for studying microphotography, but the subject also merits attention for its own inherent interest. Such a study involves pursuing the search for improved resolution to its logical limit, and is, for some minds, self-rewarding since it carries one to the brink of the unknown. Microphotography should, however, not be considered as an isolated subject, but as a part of photography itself; and the pursuit of improved resolution has engaged the attention of generations of photographic scientists.(1) As a result of their ability for revealing fine detail, experiments with microphotographic materials can reveal hitherto unrecognized phenomena, which may be adversely influencing resolution in other branches of photography. Examples are the refraction of light at the lenticular surface of a line negative and the interference of light coming from adjacent parts of an image, both of which may occur during contact printing (Chapter 10). The same investigation demonstrated the harmful effects of the common practice of applying a blocking-out medium to the surface of the negative. Microphotographic technique has necessitated various refinements of manipulation, and it would be strange if none of these found other applications. The study of microphotography also gives a deeper appreciation of the complex process of image formation, and this should help to provide a broader basis for sound technique in any field of photography.

Microphotography is, in addition, a suitable activity for the experimentally-minded amateur. The equipment required is not unduly expensive. Much of it will already be possessed by amateur microscopists, and the remainder can be constructed by simple carpentry. Amateurs should find that the straightforward application of methods described in this book will provide quite impressive results. A further attraction is that workers in this field have an unusually good chance of contributing discoveries to published knowledge. This is because most microphotographic work has been done by commercial operators, who could not afford the time to follow up any incidental observations, and tended to keep their working methods secret.

Origins of Microphotography

Whether they be in the form of paintings or models or documents, miniature reproductions of familiar objects have a fascination for the human mind. This is no recent cult, and Pollard (2) has shown that miniature writing and the printing of miniature books was practised in mediaeval times. Miniature inscriptions were even produced by the Assyrians some 5,000 years ago. During his excavation at Nineveh, Layard found hexagonal clay cylinders inscribed with characters so small that a magnifying-glass was needed to ascertain their form, and so perfect and accurately made that they could only have been produced by an elaborate instrument.

During the first half of the nineteenth century the production of minute writings was stimulated by great improvements in the resolution obtained with the microscope. Machines were made which allowed legible characters to be written with a height of about 0·0001 in. (2 microns), and dividing engines ruling as many as 50,000 lines to the inch (2,000 lines per millimetre) were constructed. The production of minute inscriptions at that time thus constituted a significant stream of human endeavour, and it is not surprising that the major (microphotographic) tributary sprang from the same period. The first recorded experiments seem to have been made in 1839 by J. B. Dancer of Manchester, within a few months of the introduction of the Daguerreotype process from France ;(3) but he did not succeed in producing the image sharpness to be expected from his objective, until Scott Archer perfected the wet-collodion process in 1851. Within a few years of this date Dancer was selling microphotographs as curios, and *Figure* 3 shows a reproduction of one of his commercial results, probably made in the period 1860–70. During the same period French manufacturers developed the technique of mounting microphotographs on one end of a glass cylinder, so that an enlarged image could be seen without further aid when the other rounded end of the cylinder is held to the eye (*Figure* 4). Microphotographs in this form were mounted in jewellery such as rings and tie-pins, and their manufacture expanded into a substantial and lucrative industry. One of the most successful operators (Dagron) employed 150 workmen, and some thirty other factories were engaged in the same business.

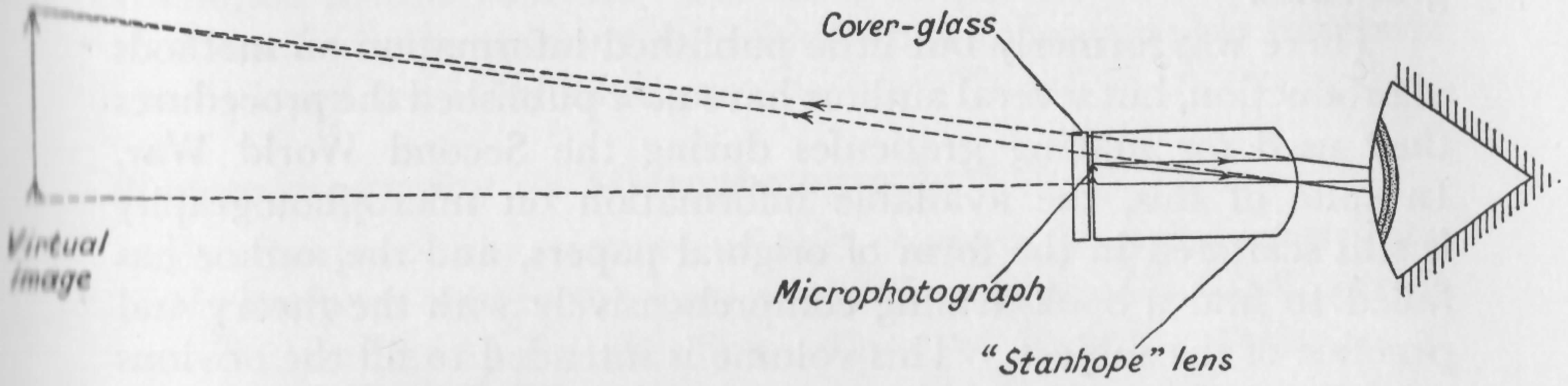


FIG. 4. *Method of viewing Microphotograph on " Stanhope " Lens.*

When the spherical end surface is placed near the eye, an enlarged virtual image is seen.

The production of minute photographs has also been a subject for competition and record breaking. One of the smallest recorded images was made by Goldberg (Chapter 3), who produced a legible image of a page of 50 lines of print within a height no greater than 0·1 mm. (0·004 in.). Now the area occupied by the text must have been about $\frac{1}{140}$ of a square millimetre, and it follows that no fewer than 87,500 such pages would be needed to fill a square inch. The text of rather less than two such pages is likely to be equivalent to the text of a page of the Bible, so that Goldberg's image was reduced to a scale corresponding to the production of 50 Bibles in a square inch. " *Bibles per square inch* ", in fact, became the unit with which competitors exuberantly measured their achievements !

Some idea of the present status of microphotography has already been given, but two important developments during the last fifteen years merit special attention. These are the first commercial production of extreme-resolution plates in 1940, and the breaking down of the secrecy which surrounded techniques used in microphotography. The availability of the commercial plates made it no longer necessary for each operator to make and coat his own emulsion, and this removed an obstacle which must have hindered the wider use of microphotography. Freer publication has been particularly noticeable with respect to instrument scales and graticules.

There was formerly but little published information on methods of production, but several authors have now published the procedures they used for making graticules during the Second World War. In spite of this, the available information on microphotography is still scattered in the form of original papers, and the author has failed to find a book dealing comprehensively with the theory and practice of the subject. This volume is intended to fill the obvious need for such a work.

Plan of the Book

The study of microphotography can be divided naturally into production techniques (Chapters 2–10) and applications (Chapters 11–13). The nine chapters on production techniques contain a not-inconsiderable mass of information, the digestion of which may prove a formidable task for readers without previous experience of the subject. This section therefore begins with an introductory chapter, which is intended to achieve two aims. The first is to provide the reader with mental links between microphotography and other better-known skills (such as photography or microscopy); the second is to permit him to gain some contact with microphotographic procedures, by working through two exercises giving quite fine images with a minimum of preliminary preparation. It is hoped that the practical experience provided by these exercises will help the reader to understand the contents of the later chapters.

The following six chapters describe sensitive materials, processing methods, objectives, focusing mechanisms, the camera and the original; and these constitute the basic "tools" with which the microphotographer operates. The way in which these tools are chosen for the task in hand is described in Chapter 9, together with the phenomenon of image formation and the methods of control required to ensure extreme sharpness. The section on technique is concluded with a microphotographic "chamber of horrors", in which are shown some of the grotesque forms which can be observed in microphotographs made by unsuitable methods.

The applications in Chapter 11 (Graticules) and Chapter 12 (Document Microphotography) both form the basis of important industries. Each could well provide the subject-matter for a separate book, but no more than a review of these topics could be attempted in this volume. The final chapter describes a number of scientific investigations in which microphotographic methods have played an invaluable part.

Photomicrography or Microphotography ?

In the preceding sections of this chapter the word *microphotography* has been used in the sense originally suggested by G. Shadbolt in 1858, and given in the first edition of Sutton's *Dictionary of Photography* published in the same year.(4) Sutton defined microphotography as "the copying of objects on an exceedingly small scale". The same authorities stated quite clearly that the reverse process of producing enlarged photographs of microscopic details should be called *photomicrography*. Microphotography has, unfortunately, been widely used in the latter sense, sometimes by scientists of world-wide reputation. The confusion is now so bad that even standard works such as the *Oxford Dictionary* indicate that microphotography is only slightly less correct than photomicrography for describing the photography of microscopic objects. For this reason "Microphotography" without a sub-title could not be used as the title of this book.

It is interesting to consider how the misuse of these words may have arisen. Confusion may have been caused by the fact that in the German language they are used in the reverse sense, apparently quite consistently. A translator unaware of the precise English definition would naturally translate "Mikrophotographie" as microphotography.

Another possible reason may be found in the fact that photomicrography has been practised far more extensively than microphotography, not infrequently by scientists with little systematic photographic knowledge using photomicrographs occasionally to assist their investigations. Now photomicrography is usually pronounced with the stress on the middle syllable, which results in the cacophonous sound of PHOTO-MI-CROGRAPHY. It is not unlikely that this has tempted some workers to misuse the word microphotography, which rolls off the tongue like a breaking wave.

Whatever the reasons for this misuse, the fact has to be faced that bad habits are notoriously difficult to lose. The immediate agreement of all English-speaking scientists to forsake the incorrect usage would only prove a palliative : it would not eradicate numerous and widespread misuses from all types of published scientific literature. The situation might be improved by the application of either of the following policies :

(*a*) English-speaking scientists might frankly admit that their careless use of these words has lost them the right to retain the original definitions. They could then adopt the German usage, and thus prevent further confusion in the future.

(*b*) The alternative is for authors to be meticulous about the example they themselves set, but inform all interested persons that the confusion has existed in the past. A student who is aware of this situation is only likely to be misled by the incorrect title during the first stage of looking-up an article. Reference to even a brief abstract should immediately show in which sense the words have been used, and hence prevent useless searches for incorrectly titled original papers.

References

(1) Brock, G. C., *Physical Aspects of Air Photography.* Longmans, Green (London), 1952.

(2) Pollard, A. F. C., " Miniature and Microscopic Documents ", *Proc. Brit. Soc. Int. Bibl.*, **5**, 43, 1943.

(3) Sidebotham, J., " On Micro-photography ", *Liverpool Phot. J.* (now *Brit. J. Phot.*), **6**, 91, 1859.

(4) (*a*) Sutton, T., *Dictionary of Photography.* Sampson Low (London), 1858.
(*b*) Chilton, L. V., " Microphotography and Photomicrography and other Terminological Inexactitudes ", *Phot. J.*, **84**, 42, 1944.

Readers wishing to study the history of microphotography more fully can consult the following articles, which contain many references to early developments :

(*a*) Luther, F., " The Earliest Experiments in Microphotography ", *Isis*, **41**, 277, 1950.

(*b*) Stevens, G. W. W., " Microphotography since 1839 ", *Phot. J.*, **90B**, 150, 1950.

CHAPTER 2

Introduction to Microphotographic Technique

Most of us experience mental obstacles to the learning of an unfamiliar technique. There is firstly the sense of strangeness, which gives rise to hesitation and doubt. In the case of microphotography it is also rather natural to presume that the work is incredibly difficult. This assumption is probably related to our knowledge of the skill and patience needed for making models or miniatures of any kind. It is, moreover, not easy to appreciate the full significance of technical writing unless the reader has himself had some experience in the particular field of work.

The purpose of this chapter is to provide a bridge across these obstacles. Its intention is to show that :

(1) the unfamiliarity can be thawed by comparisons of microphotography with other better-known techniques,
(2) with suitable apparatus and working methods microphotography is no more difficult than the securing of good quality in photographic prints,
(3) quite fine images can be made with surprisingly little preliminary preparation.

Two practical exercises have been included to achieve the third of these objectives. The reader with little practical experience in microphotography is most strongly advised to work through these exercises, before reading the more detailed technical chapters of this book. The experience and direct contact with microphotographic materials thereby gained should make it easier to appreciate the technical points made in the following chapters.

Relationship to Amateur Photography

Most of the photographs made to-day consist of greatly reduced images of the original subject. The image of miles of country seen from a hill may, for instance, be recorded on a negative only $2\frac{1}{4}$ in.

(56 mm.) high. Even smaller images with a height less than half an inch (12·5 mm.) are made on amateur ciné films and in the "Minox" camera, and these represent the useful working limit of reduction that is practicable for "instantaneous" photography. Much greater reduction would cause intolerable loss of sharpness unless much slower emulsions are used.

The making of microphotographs is, in principle, no different from the taking of ordinary photographs, but the scale of the images is drastically reduced. The loss of sharpness which should result from this further reduction of image size is combated by using very slow emulsions with much finer grain, and by employing only the centre of the field of the objective. These measures necessitate a number of restrictions, which must be accepted as inevitable inconveniences. The slow emulsions used require relatively long exposures and high levels of illumination. Only still originals can, therefore, be readily used for microphotography, and the camera must be fixed firmly so that the aerial image cannot move with respect to the emulsion during the exposure. Such restrictions are part of the price which has to be paid for extreme resolution.

Resemblance to Microscopy and Photomicrography

Microphotography, or the art of producing minute images from large originals, is essentially the reverse of microscopy or photomicrography, which are concerned with the production of greatly magnified images of minute objects. Both techniques are necessarily concerned with the resolution, useful flat field and methods of using objectives. The microscopist undertaking photomicrography will find other similarities, and books on photomicrography and general microscopy contain much information of use to the microphotographer. Discretion is, of course, needed in interpreting this information in the light of the essential differences between these arts. Photographic emulsions used for microphotography are of little use for photomicrography. When a 4-mm. ($\frac{1}{6}$-in.) objective giving a resolution of 2,500 lines/mm. is used to project an image enlarged 500 times, the resolution of the enlarged aerial image cannot possibly exceed 5 lines/mm. The resolution of any but the fastest emulsions should thus prove adequate, and it would be futile to use an emulsion giving 1,000 lines/mm. and requiring very long exposures.

Basic Arrangement for Microphotography

The equipment used for microphotography can vary greatly in detail, but the basic arrangement always remains the same. It is, therefore, convenient to define the various components of this basic arrangement.

The *original,* which may be a transparency illuminated from behind, or a drawing or photographic print, or occasionally even a solid object, is located at the *object plane* (*Figure* 5). The centre of the original is normally placed on the *axis* of the lens or objective.

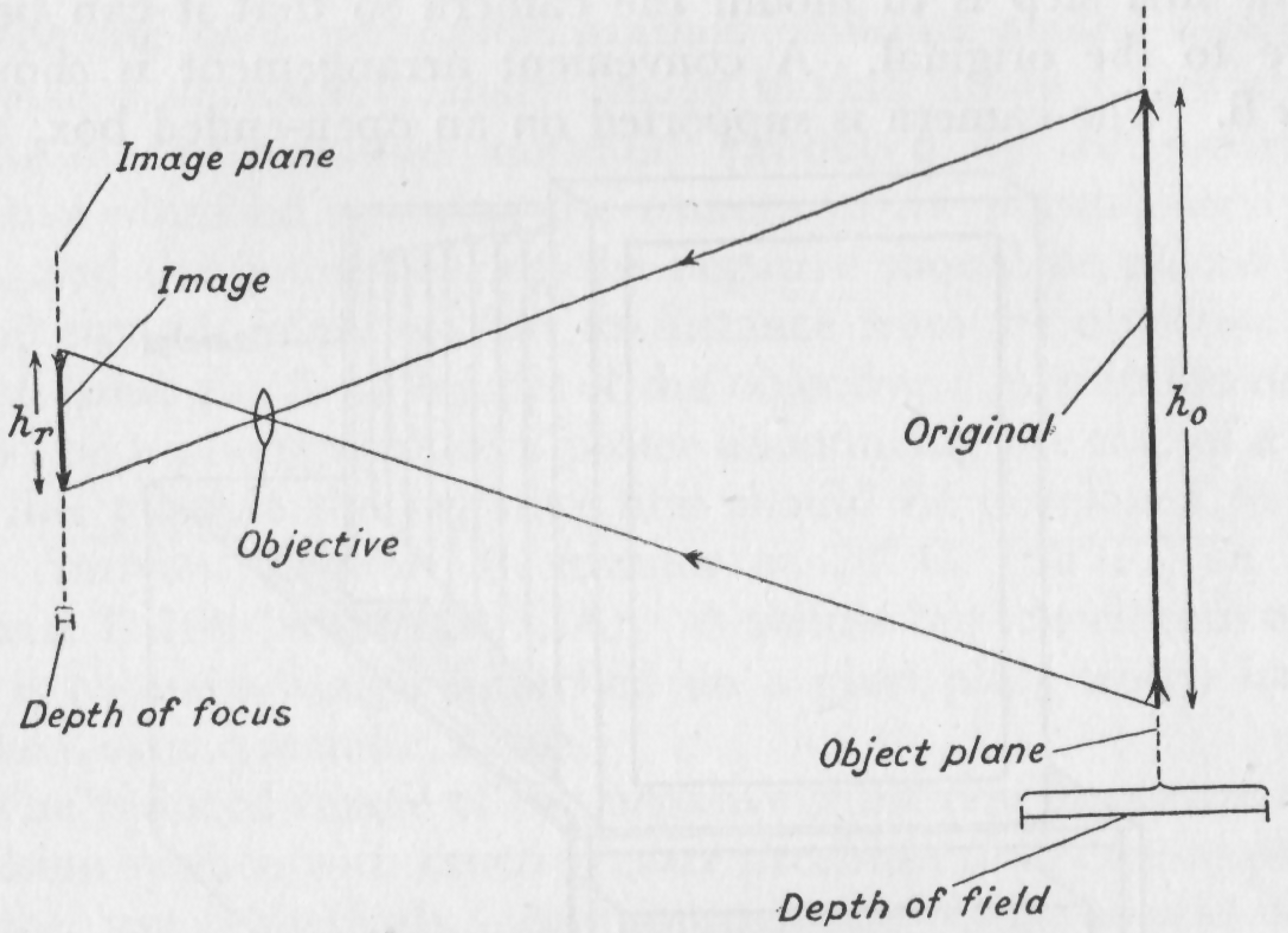


FIG. 5. *Basic Arrangement for Microphotography.*

The degree of reduction $\left(\frac{ho}{hr}\right)$ equals the objective-to-object-plane distance, divided by the objective-to-image-plane distance.

The *objective* may be a photographic lens or a telescope or microscope objective, and the degree of reduction may (if desired) be increased by an ocular or eyepiece. The emulsion of the sensitive material lies in the *image plane.* Any tolerance in the position of the object plane, within which no deterioration of image sharpness can be seen, is known as the *depth of field.* The corresponding but much smaller tolerance in the position of the image plane is known as the *depth of focus.* These definitions will be used throughout the rest of this book.

Preliminary Exercises in Microphotography

I. *Obtaining the Optimum Resolution from any Available Camera*

A practical obstacle in the way of a new-comer to microphotography was, in the past, the necessity for making his own sensitive material. This is no longer necessary, since concentrated Lippmann plates are now commercially available (Chapter 3). Images much finer than those obtainable on " fine-grain " negative films can be made by using these plates with any snapshot camera fitted with a good objective.

The first step is to mount the camera so that it can be held square to the original. A convenient arrangement is shown in *Figure* 6. The camera is supported on an open-ended box, and is held square by one or more battens fixed to the top of the box. It is held firmly by a bolt * passing through a hole in the top of the box, and screwed into the tripod socket of the camera. A brick is placed in the box to steady it and lessen the risk of accidental movement. The box is placed squarely against a straight edge attached to a firm table, and the original is held on a vertical board mounted at right angles to the straight edge, and is placed so that the axis of the lens goes through the centre of the original. A transparency is the best type of original to use, and is illuminated by placing a No. 1. Photoflood lamp about 4 inches (10 cm.) behind a " flashed " opal, which is mounted over an aperture in the board behind the transparency (negative).

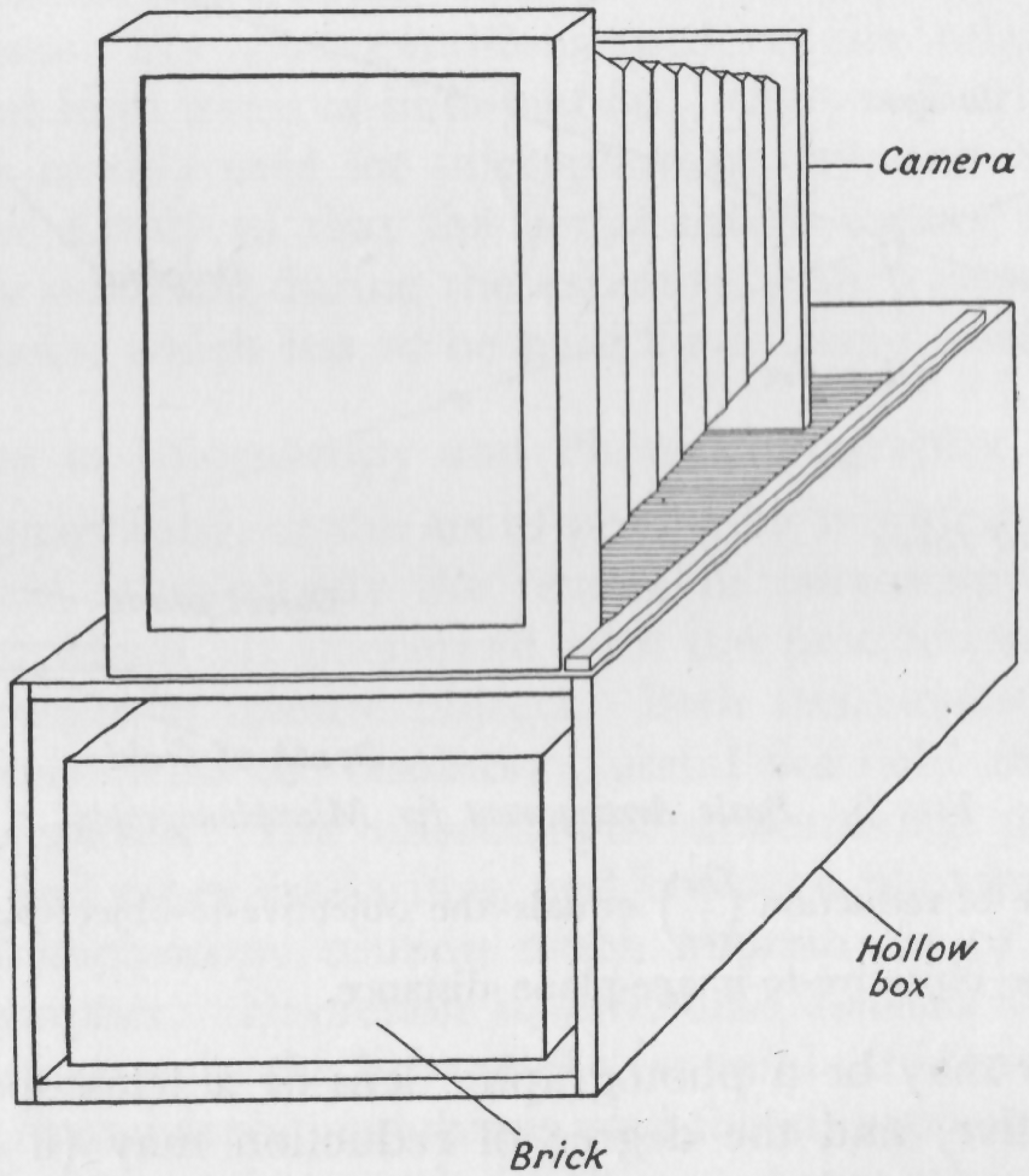


FIG. 6. *Mounting of Camera on Box.*

The use of a microphotographic emulsion should enable one to make a reasonably sharp image having about a tenth of the height of the negatives normally produced by the camera. A negative obtained by using the camera in the normal way can be used, and the board bearing the negative should be placed square to the straight edge, so that its distance from the objective equals eleven times the focal length of the objective. A suitable negative would be a photograph of a poster announcing the sale of a house. For this purpose the negative film should be developed to give a high contrast, say for 10 minutes at 20° C. (68° F.) in Kodak formula D.19b (Appendix I, A). A simple but less elegant alternative is to use a design scratched on a glass plate which has been smoked over a candle flame.

The reduced image of the negative must now be focused at the emulsion surface with much greater precision than can be obtained by the usual methods. An approximate focus should first be obtained by setting the focusing scale, or by focusing on a ground-glass screen. The precise focus is then found by altering the distance from the camera to the negative, with the camera setting unchanged. With an image-reduction of ten diameters the alterations in objective-to-image distance will be one-hundredth of any small change in the distance from the camera to the negative. Thus a change of $\frac{1}{10}$ in. (2·5 mm.) in the camera-to-negative distance will change the objective-to-image distance by one thousandth of an inch (25 microns).

Before starting the exposures, make the following preparations. Firstly decide how the plates are to be loaded into the camera. If a plate camera is used, employ only one plate-holder in order to obtain the best possible uniformity of registration. Roll-film cameras can usually be used by loading in the darkroom with a plate laid against the aperture which holds the film in register. Standard plates may not be of suitable size, and it may be necessary to cut them to the size required. An index mark should be made on the side of the box supporting the camera, and opposite this mark rule a number of lines $\frac{1}{10}$ in. (2·5 mm.) apart on the straight edge. Two pieces of cardboard should be used as " shutters ", and one should have an aperture one-fifth of the height and width of the negative cut from the centre of the card.

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* The bolt should be $\frac{1}{4}$ in. Whitworth for " British " sockets or $\frac{3}{8}$ in. Whitworth for " Continental " sockets. To prevent risk of damage to the camera, the bolt should be cut so that not more than three threads can be engaged. American Standard Z/38·4·1—1942 specifies the thread as $\frac{1}{4}$—20—N.C. 1.R.H.

Adjust the focus of the camera by the method normally used, and set the lens diaphragm to one or two " stops " below full aperture. Then determine the correct exposure by exposing a plate while the exposure time is progressively increased across the negative. For this purpose :

expose the whole negative for 10 seconds,
cover a narrow strip of the negative with the card and expose the rest of the negative for a further 10 seconds,
with the card moved in stages across the negative, give further exposure times of 20, 40, 80 . . . seconds as required.

On development, this plate will then show successive strips exposed for 10, 20, 40, 80, 160 . . . seconds. When viewing it to find the correct exposure, one should note that the blackness of fine lines increases with improvement of focus as well as with increased exposure (see Chapter 9). Thus if the images are not very sharp, an exposure giving a rather faint image should be chosen.

Inspection of the most correctly-exposed part of this plate with a powerful magnifier or microscope is likely to show that it is not very sharp. This is because the sensitivity of the normal focusing method is insufficient for such fine-grain plates. The next step is therefore to make a series of exposures on one plate with the exposure time already chosen, and with the camera-to-negative distance changed by one division of the scale between exposures. The images are kept separate by placing the aperture in the second card in front of different parts of the negative for each exposure, so that a series of images are formed side by side, with each image reproducing only part of the negative at a slightly different focus.

When viewed with sufficient magnification the developed images may show a gradual improvement, followed by a gradual deterioration as the focus is changed. This is a satisfactory result, since it indicates that the range of the test includes the optimum focus. The focusing test may, however, only show an improvement of focus from one end to the other. In this case it is better to make another test, starting with two or three positions giving the sharpest images in the first test, and extending the range of distances further. Exposures made at the best conditions indicated by the focusing test should give images much finer than the camera can produce on its customary negative material.

Now this exercise demands patience and care and concentration, but there is nothing *really difficult* about it. The same type of procedure can also be used for making high-quality intermediate negatives needed for ultra-fine microphotographs, and (if the camera objective is sufficiently good) for making eyepiece scales.

II. *Removal of the Limitation set by Photographic Objectives*

Close examination with a microscope will show that the pictures obtained in the first exercise start to look unsharp before sufficient magnification is used to make the graininess obtrusive. It is, in fact, apparent that the resolution has been limited by the aberrations of the photographic objective. A further substantial improvement of sharpness can be obtained by using a microscope objective, since the image on the axis should be practically free from aberration.

For this exercise it is advisable to use a low-power achromatic objective of focal length 1 in. (25 mm.), or $\frac{2}{3}$ in. (16 mm.). The main problem is how to obtain sufficiently exact focus, since the high aperture and resolution of such an objective means that focusing will be even more critical than in Exercise I. This can be done, with a minimum of preparation, by using a microscope as the " camera ". Remove the eyepiece and objective from the microscope, and turn the barrel to the horizontal position. Mount the microscope on a small board, so that the axis of the barrel will pass through the centre of the negative-holder when the board is pressed against the straight edge used in Exercise I. With this type of objective attractive images only $\frac{1}{25}$ in. (1 mm.) high can be made, and the following approximate distances from the negative to the objective will be needed.

TABLE I

Distance of Negative for Production of 1-mm. Image

Height of negative	*Focal length of objective*	*Distance from negative to objective*	
		Inches	*Centimetres*
1 in. (25 mm.)	1 in. (25 mm.)	26	65
2¼ in. (57 mm.)	"	59	140
1 in. (25 mm.)	⅝ in. (16 mm.)	17	40
2¼ in. (57 mm.)	"	36	95

When the negative-holder has been placed at the appropriate distance, the different parts of the apparatus should be secured with small pieces of " Plasticine ". This lessens the chance of accidental displacement, or of the resolution being spoilt by vibration.

The thickness of ordinary photographic plates is not sufficiently constant to ensure that the emulsion is always sharply focused when successive plates are placed, emulsion side up, on the stage. The focus in this exercise will therefore be found visually for each plate, by using the microscope condenser to illuminate one end of the plate with red light, while observing the enlarged image of the emulsion surface projected at the plane of the negative-holder. The action of the objective is reversible, so that a reduced image of the negative must be sharply focused at the emulsion surface, when an enlarged image of the emulsion is focused on the plane of the negative.

A few simple precautions are needed to prevent the plates from being fogged all over. Pieces of blackened cardboard with holes cut in them should be fitted snugly round the condenser and objective, so that direct light from the exposing or focusing illuminants cannot reach the emulsion. The work-room should be darkened before placing the plate on the stage, and a black cloth should then be pinned round the microscope. With emulsions as slow as these, this method is effective in preventing fogging, even when a Photoflood lamp is used for exposing. Finally the substage condenser should be fitted with a red filter, such as a " Wratten " No. 25

tri-colour red. This transmits ample light for visual focusing, but will prevent the images from being spoiled by fog produced during focusing.

The remainder of the work should be done in a darkened room illuminated by the safelight recommended for the plates being used. Take a strip of plate about 1 in. (25 mm.) wide and about 3 in. (75 mm.) long, and make several ink marks on the emulsion surface at one end. When the ink is dry, place the plate *emulsion-side-up* on the stage of the microscope and with the ink marks opposite the objective. Arrange the clips on the stage so that the plate is firmly held, but can be moved sideways without rocking. Replace the black cloth around the microscope, insert an eyepiece in the tube, and illuminate the condenser with a 25-watt " Pearl " lamp. Observe the emulsion surface through the eyepiece, and move the plate until a part of one of the ink marks showing really fine detail (such as crystals or a minute scratch) is right in the centre of the field. The eyepiece is then removed, and the objective is focused so that a sharp image of the ink mark is projected on the plane of the negative. For this purpose, place a clean sheet of glass, on which a few scratches have been made, in the negative-holder and examine from behind with a focusing magnifier. Keep the eye constantly focused on the scratches, and focus the microscope until a sharp image of the ink marks on the photographic plate can also be seen. When both the scratches and the ink marks can be seen at the same instant, the emulsion surface is focused on the object plane, and conversely a reduced image of the object plane will be focused on the emulsion surface. It is then only necessary to place a negative and the opal in the negative-holder, move the plate sideways by an inch (25 mm.) to bring an unspoiled area of emulsion under the objective, and make a number of images with increasing exposure times, sliding the plate a small distance sideways after each exposure.

The exposure of two or three strips of plate in this way, re-focusing for each plate, should give some images of fair quality, in which at least part of the image is really sharp. (Lack of uniformity of sharpness may be due to poor alignment of the equipment, incorrect centring of the image on the axis of the objective or lack of flatness of the field of the objective.) It should, nevertheless, be apparent that the lens and emulsion when properly adjusted can reproduce a page of a novel (say 400 words) at this size so clearly that the serifs on the letters can be clearly seen. This is in spite of a degree of reduction equivalent to copying a long novel of 800 pages in a square inch !

Refinement of Procedure to give Adequate Control and Precision

The second exercise has been designed to permit fairly fine images to be made with a minimum of preparation, but it cannot be guaranteed to give completely consistent results, nor is the method suitable for making very fine images. This method suffers from the following intrinsic defects :

(i) Focusing and exposure of the emulsion are effected with lights of different wavelength, so that an error could be introduced by chromatic aberration in the objective (see Chapter 5).

(ii) The objective must be re-focused for each plate, and this is likely to introduce some variation of image sharpness.

(iii) The method depends on the thickness of the plate being sufficiently uniform to prevent the focus from altering as the plate is moved sideways.

None of these objections is too serious when making a few moderately fine images as an experiment. The effect of chromatic aberration can be compensated by moving the negative-holder a small distance *after* the objective has been focused. According to the properties of the lens used, the distance may have to be increased or decreased. The other two defects are more serious, and their influence can only be corrected by using equipment which locates the plate by the emulsion surface. The design and operation of this equipment is discussed in Chapter 6.

The production of large numbers of microphotographs of consistent quality, or the making of very fine images, depends on the methods used to bring the process under strict control. Descriptions of the apparatus, materials and techniques for doing this form the subject-matter of the chapters in this book which are devoted to technique.

Units for Measuring Small Dimensions

In concluding the chapter, mention should be made of the

units conveniently used for measuring the dimensions of microphotographic images. These are the thousandth part of an inch, often called a " *thou* " * and written 0·001 in., and the thousandth part of a millimetre, which is called a " *micron* " and is represented by the symbol " μ ". The size of these units can be appreciated by comparing them to a human hair, whose thickness is about 2 " thou " or 50 μ. It is interesting to note that the micron is not much greater than the wavelength of visible light, which ranges from 0·4 μ (in the violet) to 0·7 μ (in the red); but wavelengths are more commonly measured by the *Ångstrom Unit* (written Å.), which equals one ten-thousandth of a micron. The visible spectrum thus extends from 4,000 to 7,000 Å.

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* A thousandth of an inch is called a " thou " in Great Britain, but a " mil " in the United States of America.

CHAPTER 3

The Sensitive Material

THE CHOICE of a sensitive emulsion may tend to be confused by the fact that microphotography comprises three related but essentially different arts. These are :

(i) the making of minute individual images whose height may be no more than a few thousandths of an inch (100 microns or so),

(ii) the commercial production of reduced document copies in which the larger dimension of a copy of a page is rarely less than $\frac{1}{4}$–$\frac{1}{2}$ in. (6–12 mm.),

(iii) the production of instrument scales which require an extremely sharp image, even if the total dimensions of the scale are relatively large.

In the first and third fields the ability of the emulsion to record fine detail (resolving power) is all-important, but photographic speed is only a secondary consideration. This is because the original can take the form of a transparency, which permits the use of illuminating systems requiring a tolerably brief exposure even with a very slow emulsion.(1)

Emulsions for Document Microphotography

In the second field, however, the convenient operation of commercial document-copying processes demands that the images should be produced by direct reduction from opaque documents which are photographed by reflected light. Much of the light reflected from the document never enters the objective, and the volume of work precludes the use for each image of an exposure longer than a few seconds. These restrictions demand the use of an emulsion whose speed is approximately equivalent to that of a " bromide " enlarging paper. This necessity for specifying a minimum practicable level of speed constitutes an essential difference between commercial document microphotography and the other applications.

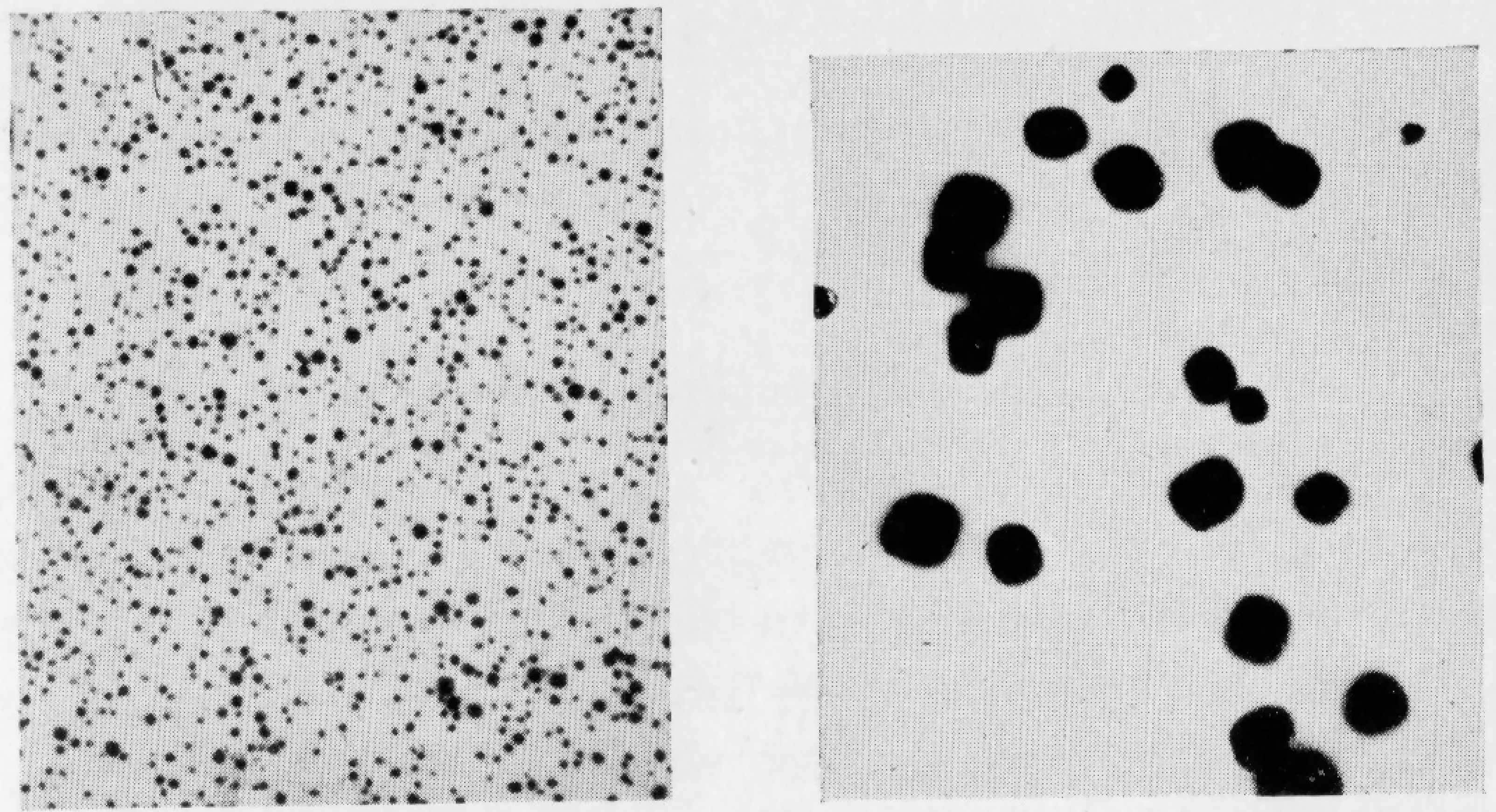

(a) (b)

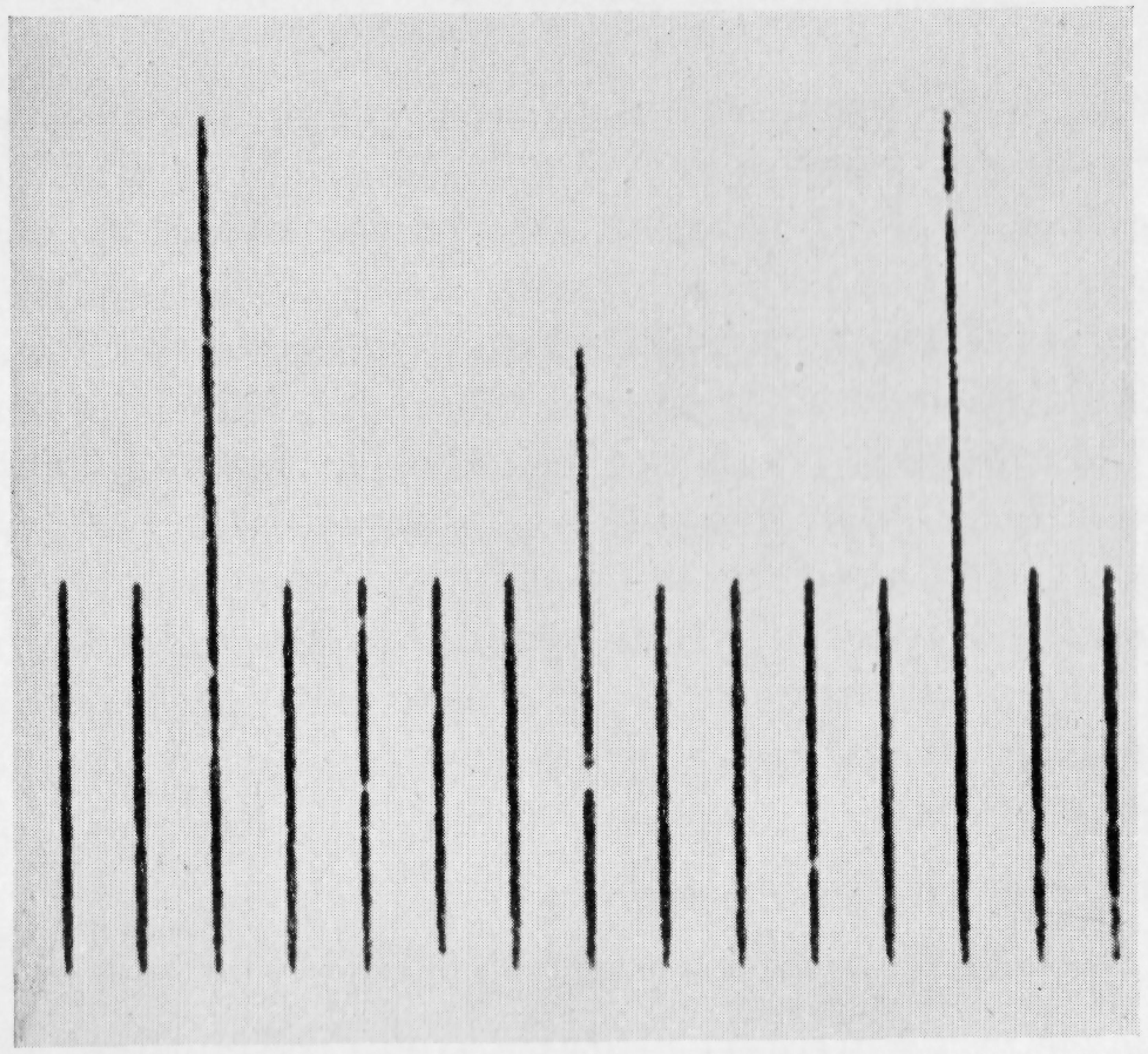
FIG. 7. *Grains of Concentrated-Lippmann and Document-copying Emulsions.*

(*a*) Electron-micrograph (×10,000) of undeveloped Maximum Resolution emulsion.

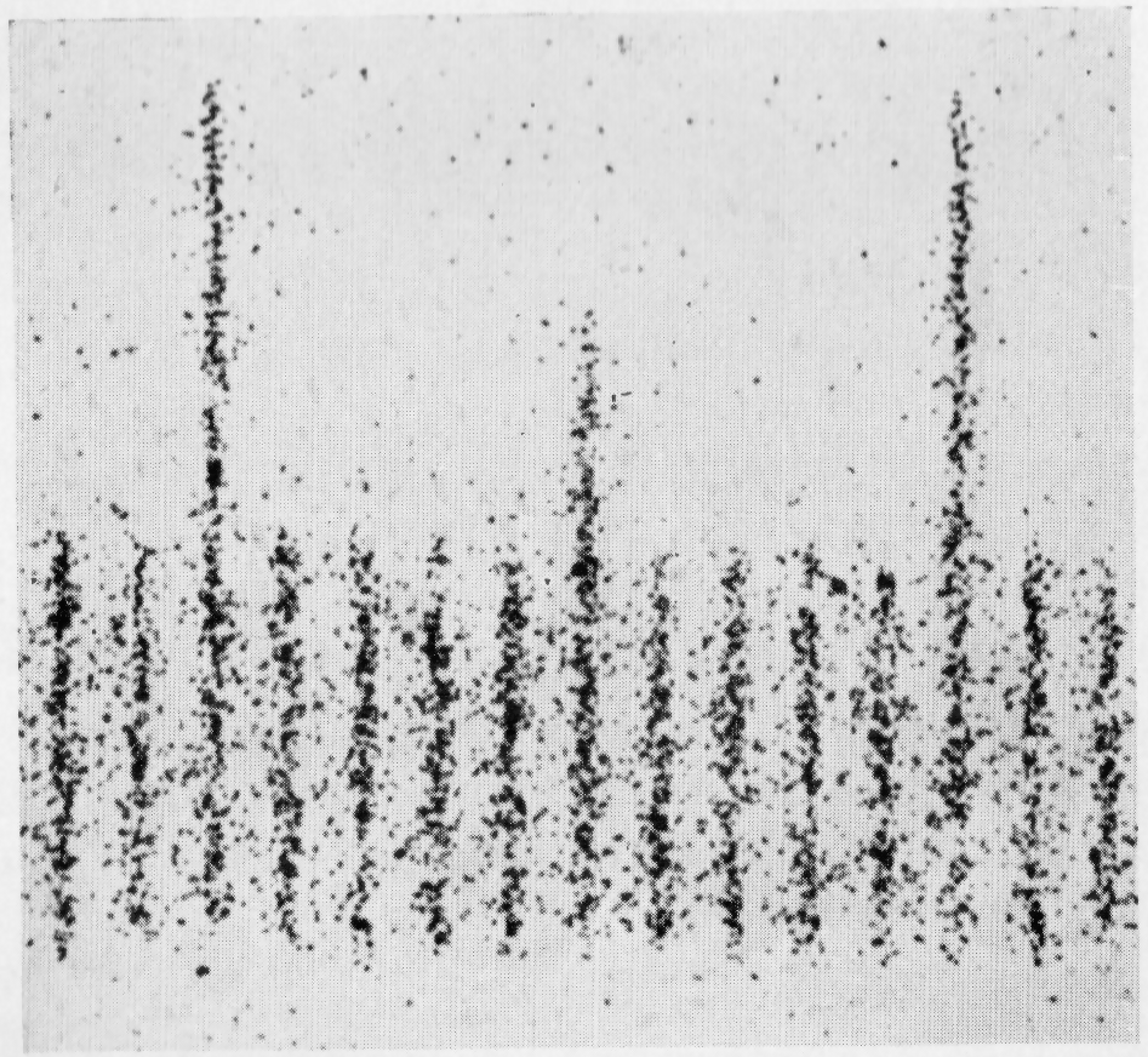
(*b*) Grains of document-copying emulsion at same magnification.

Courtesy of Miss J. Tabor. Kodak Research Laboratories, Harrow.

[Facing p. 20.



(*a*) Image on Maximum Resolution plate (×540). The only sign of graininess is a slight roughening of the edges of the lines.



(*b*) Similar image on document-copying emulsion. Note how turbidity has spread the lines and reduced the contrast.

FIG. 8. *Sharpness given by Concentrated-Lippmann and Document-copying Emulsions*

[*Facing p. 21.*

The setting of the speed at this relatively high level indicates that only silver-halide " dry-plate " emulsions can be used. Furthermore, the speed requirement, for reasons discussed later, also limits the fineness of grain which can be used. Many photographic manufacturers now produce films specially designed for this purpose (Burroughs " Microfilm ", Gevaert " Duplo ", Ilford " Microneg ", Kodak " Micro-File ", and so on). These are all designed to provide relatively high resolution combined with the necessary speed, have grain diameters lying mainly in the range from 0·2 to 0·6 microns, and give fairly high contrast. An important requirement for many applications is that the film base should resist deterioration on keeping, and cellulose-nitrate bases should not be used for this purpose.

Materials for Extreme Resolution

A much wider range of sensitive materials can be used for the other applications, since this work permits even the slowest photographic emulsions to be exposed adequately without great inconvenience. Silver-halide-gelatin emulsions can be used with grain sizes down to the lowest limit it is practicable to make.

The concentrated-Lippmann emulsions, for instance, have grain diameters in the range 0·01 to 0·1 μ (*Figure* 7). An impression of the improved resolution this permits is given in *Figure* 8. Other materials which can be used are :

" wet " collodion,
silver salt print-out emulsions,
bichromated colloids,
diazonium salts imbibed by a transparent base—particularly when incorporated with a mercury salt,
silver albuminate,
and (possibly) dye-bleach materials and light-sensitive glass.

In spite of this wide variety, these materials suitable for extreme resolution all have certain properties in common. In the following pages we shall consider these properties which are important for obtaining extreme resolution.

Properties of Importance for Extreme Resolution

The Support

The support, whether it be glass, paper or film, can do much to hinder or assist the potential resolution of any microphotographic emulsion. The surface of a coated emulsion normally follows the contours of the surface on which it is coated, although it may partly fill in the hollows. Roughness of the emulsion surface produced by any cause will tend to have a disruptive effect on the image, which becomes increasingly objectionable as progressively smaller images are produced. The surface of the base should therefore be smooth—if it is " glass " smooth so much the better. Paper bases should be baryta coated and have a " glossy " finish. The surface finish of transparent film or glass plates is usually satisfactory for most purposes.

The optical properties of the support are important. With transparent supports such as glass or film, the light transmitted by the emulsion can travel sideways as a result of internal reflection from the back surface of the support (*Figure* 9*a*). This is ordinary *halation*, and is normally prevented by application of a light-absorbing layer (or *backing*) in optical contact with the back of the support.(2) Paper and other light-scattering bases cause the trouble

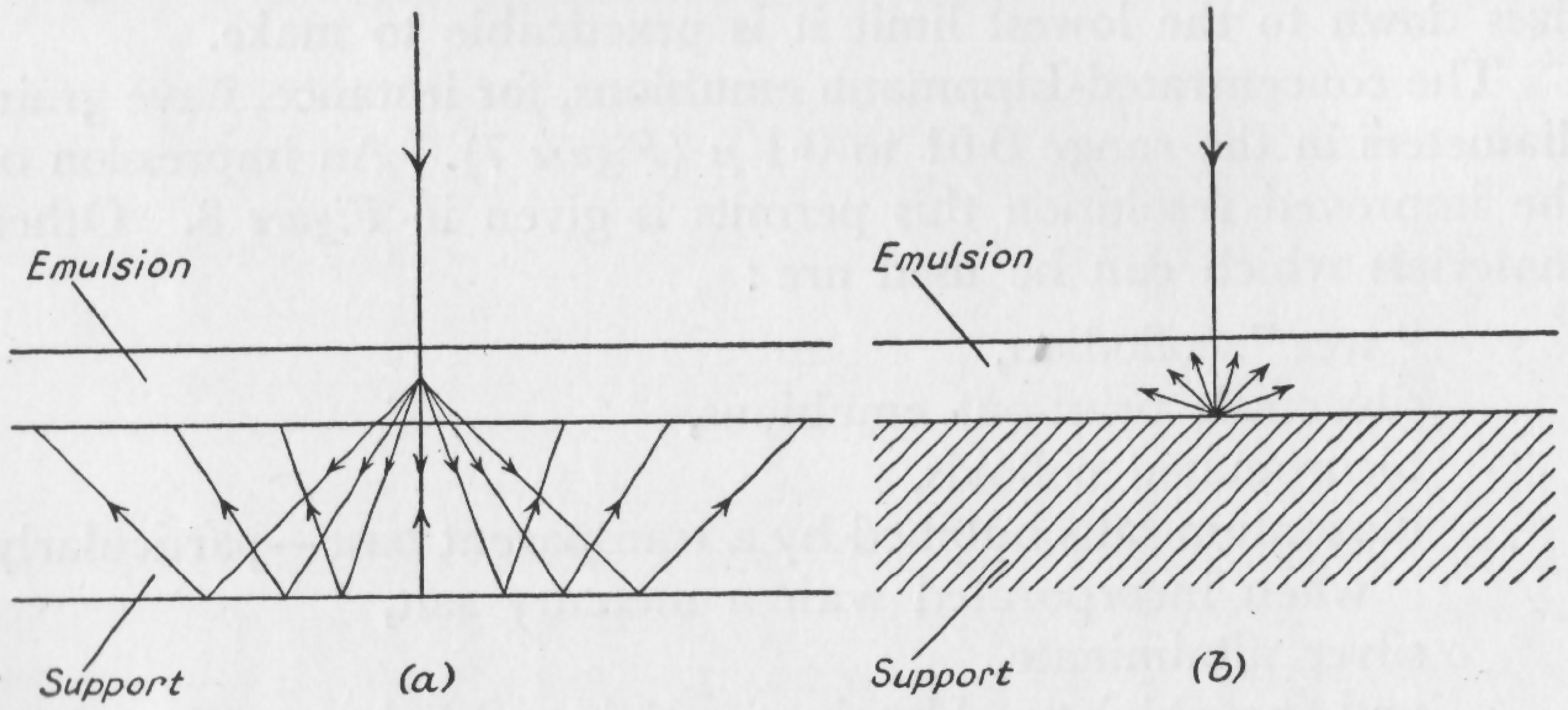


FIG. 9. *Halation.*

(*a*) With slightly-scattering emulsion on transparent support.
(*b*) With transparent emulsion on light-scattering support.

in a different way, by providing a diffuse reflector just below the emulsion surface (*Figure* 9*b*). The cure is to apply a light-absorbing layer containing a bleachable dye or pigment between the emulsion and the base. Either type of halation is most likely to prove harmful with emulsions whose unexposed layer has a low opacity

for actinic light, and may not be troublesome if the layer absorbs so strongly that the image is confined to the emulsion surface.

The optical properties of the base also influence the ease with which images can be viewed. Thus really minute images are only seen to the best advantage when illuminated by a correctly-focused beam of transmitted light. These conditions cannot be satisfied with images on paper, and it is also not easy to provide sufficient illumination for the inspection of images on paper at a really high magnification. The reduction of a page of a book to a height of about one quarter of an inch (6 mm.) is approaching the useful limit for images on paper. With really minute images on transparent base, the thickness of the support should not be sufficient to prevent correct focusing of the substage condenser of a microscope. Plates used for producing images whose height is equal to or less than 0·5 mm. (0·02 in.) should for this reason not be thicker than 1 mm. (0·04 in.).

Whereas the optical properties of the base have a direct effect on the quality of the image, the mechanical properties influence the ease with which correct focus can be obtained. A convenient method for obtaining correct focus is to press the emulsion surface against suitable locating surfaces (see Chapter 6). Flexible bases such as film or paper need to be clamped on either side of the exposed region, so that an area corresponding to the image is held flat without bulging. The use of a rigid support, however, means that lack of flatness of the emulsion surface cannot be readily counteracted by mechanical pressure. The influence of such unevenness depends on the distance spanned by the locating surfaces (Chapter 6). It is impossible to make any generally valid statement about the flatness of photographic glass plates, but commercial-quality plates may depart from flatness by a thousandth of an inch (25 microns) or more over a $6\frac{1}{2} \times 4\frac{3}{4}$ in. (16 × 12 cm.) plate. The unevenness often consists of a bowing or a series of waves, but the curvature of the plate surface is normally so gentle that little trouble is likely to be experienced when the emulsion is pressed against locating surfaces within half an inch (12 mm.) of the image. Difficulties due to unevenness mainly arise when contact printing, or when images are made on larger plates which are located an inch or more from the image. In such cases superior results should be obtained with " plate " glass, since this is ground and polished. In extreme cases optically-worked glass, which should have a surface flat to a quarter of a wavelength of light (say 0·15 μ), can be used. The maximum possible error is then well within the depth of focus of a $\frac{1}{6}$-in (4-mm.) microscope objective (Chapter 5).

The choice of a support will also be influenced by such factors as dimensional stability, freedom from flaws and resistance to damage and breaking, and convenience in storing and viewing the images. While some readers may have special reasons for preferring film or paper, the beginner is advised to use glass plates. They are easy to coat in small quantities, and the images do not tend to go out of focus when viewing them with a microscope.

Emulsions

The light-sensitive systems used in microphotography mostly consist of a photosensitive compound contained by an inert colloid medium. We shall, for convenience, refer to these systems as " emulsions ".*

The Colloid Binding Medium

The colloid binding medium must be capable of giving a substantially flat, glass-clear layer, having no visible discrete structure. Such layers are most usually produced by applying a solution of the colloid (which solution also often contains the photosensitive substance) to the support, and then allowing the solvent to evaporate, with or without gelling of the colloid. The conditions must be adjusted to prevent the upper surface forming a semi-rigid skin, while the lower layers are still quite fluid. The skin may otherwise crumple to form a net-like " reticulation " pattern having a disastrous effect on the appearance of the image. With gelatin emulsions the layer is formed by " setting " or gelling of the gelatin, and skin formation is prevented by standing the plates coated with warm emulsion on a chilled slab. This ensures that the lower layers set first. In collodion " emulsions " skin formation is avoided by use of a suitable mixture of high-boiling and low-boiling solvents. The solvents must also be blended so as to avoid too rapid cooling by evaporation, since this can lead to condensation of water accompanied by formation of a milky layer harmful to

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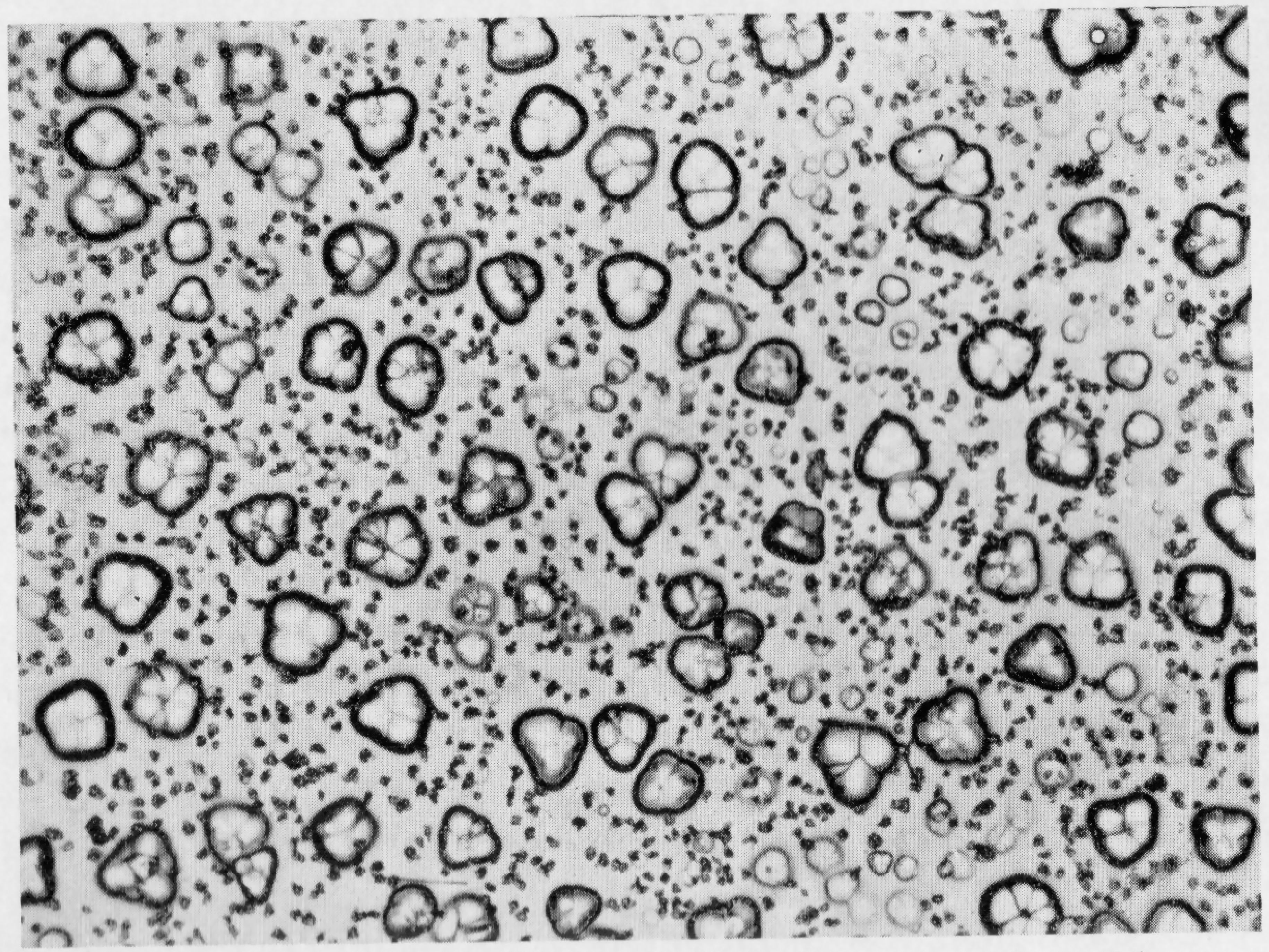
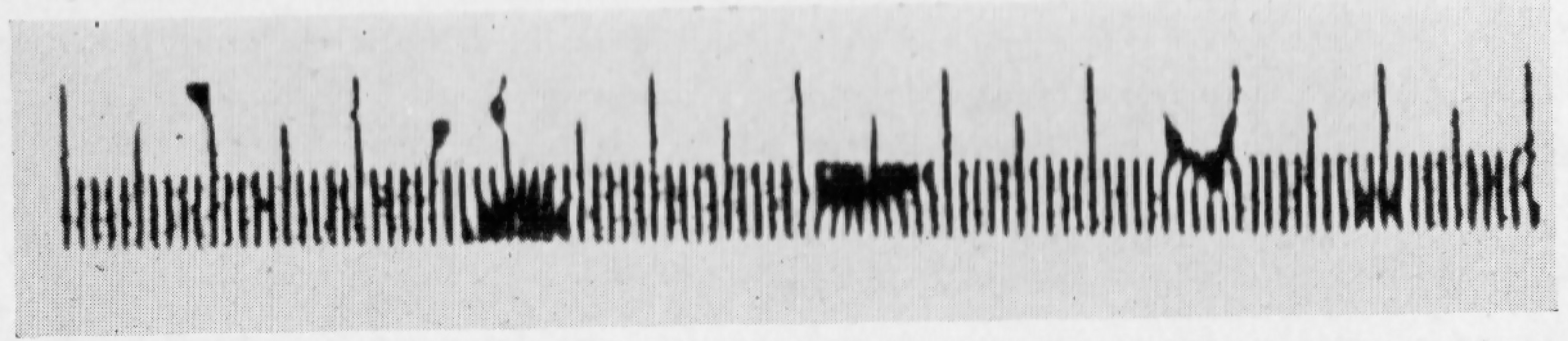
* This is not chemically correct, but the use of this word to describe silver-halide-gelatin systems is universally recognized.



(*a*) Potassium nitrate crystals (×96) formed in unwashed emulsion coated on plates.



(*b*) Coarse and fine distortions of image, corresponding to large and small crystals.

FIG. 10. *Crystals in Unwashed Emulsion.*

[*Facing p.* 25.

extreme resolution. Disruption of the image can also be caused by crystallization of the soluble salts left in a silver-salt emulsion after precipitation of the silver halides (*Figure* 10). This is avoided by washing the set emulsion either after precipitation, or after the plates have been coated but not dried. In collodion emulsions the trouble can be avoided by using deliquescent salts showing little tendency to crystallize. Thus Goldberg ⁽¹⁾ chose lithium salts for his print-out emulsions, since these salts are not only soluble in alcohol-ether mixtures, but show less tendency to crystallize when the layer dries.

In some cases the support itself constitutes the binding medium. In the Philips' mercury-diazonium process a band of " Cellophane " is sensitized by bathing in a solution of the photosensitive compounds.⁽³⁾ Even glass itself can now be made photosensitive, and in this case the glass constitutes both the photosensitive compound, the binding medium and the support !

A few cases have also been noted in which no binding medium at all has been used. Burmistrov ⁽⁴⁾ described a process depending on the adsorption of silver compounds directly to the surface of glass, but his process does not seem to have got beyond the experimental stage. It has also been supposed that the secret process used to make Rheinberg's " filmless " graticules ⁽⁵⁾ may have been of the same type.

The Thickness of the Emulsion Layer

It is natural to suppose that a very thin emulsion layer is required for extreme resolution, but this is not always true. Thus a thin emulsion layer is not essential when a high-aperture objective is focused right in the surface of a transparent layer such as a concentrated-Lippmann emulsion, and is used to produce fine black lines on a clear background. The small depth of focus resulting from the high aperture of the objective causes the image to be confined to the upper layers of the emulsion (Chapter 9). This advantageous result is not obtained when the width of the lines is large compared with the emulsion thickness, nor when the final image is a " negative " with clear lines on a dark background. A thin emulsion layer is unnecessary when the emulsion absorbs actinic light very strongly. (See section of this chapter dealing with " Optical Properties of the Emulsion ".)

A thin emulsion layer is necessary when the image is produced by a "direct-positive" process, in which the effect of the light action is to prevent the formation of a dark image. In such cases the dark parts of the image are formed by blackening of the unaffected part of the photosensitive compound throughout the entire emulsion thickness. It follows that a really sharp fine line can only be produced if the emulsion thickness is no greater than the depth of focus of the objective used to form the image (see Chapter 5). Examples of such processes are the reversal of silver-halide emulsions by bleaching and reblackening after development of a negative image, and the direct-positive diazotype process in which the dye is formed from the diazonium salt which has not been decomposed by the action of light.

The emulsion thickness is also of critical importance in processes where the image is formed by the light action resulting in a difference in the solubility of the colloid medium. This is because of the mechanical behaviour of the areas forming the image during and after the washing-out of the more soluble areas.

If we take a cube of an unswollen colloid, and allow it to swell in a solvent, it will tend to expand uniformly; so that all three dimensions are increased to the same extent (*Figure* 11). A thin layer of colloid coated on a rigid support behaves quite differently, since it can only expand upwards so long as it adheres to the support (*Figure* 11*b*). The swollen layer is, in fact, in a stressed condition, because its tendency to swell laterally is prevented by adhesion to the support. With the relatively thick coating applied to commercial plates this stress sometimes causes wrinkling of the emulsion, or "reticulation". Consider what happens during the washing-out of a stencil image in such a stressed layer. In the case of a thin clear line in a blackened (or hardened) background, the washing-out of part of the material of the line will allow the edges of the adjacent hardened areas to lean inwards (*Figure* 12). This may sometimes be so pronounced that opposite sides touch, and no further washing-out can occur. A different result is observed when the stencil image consists of fine lines. Before washing off, the

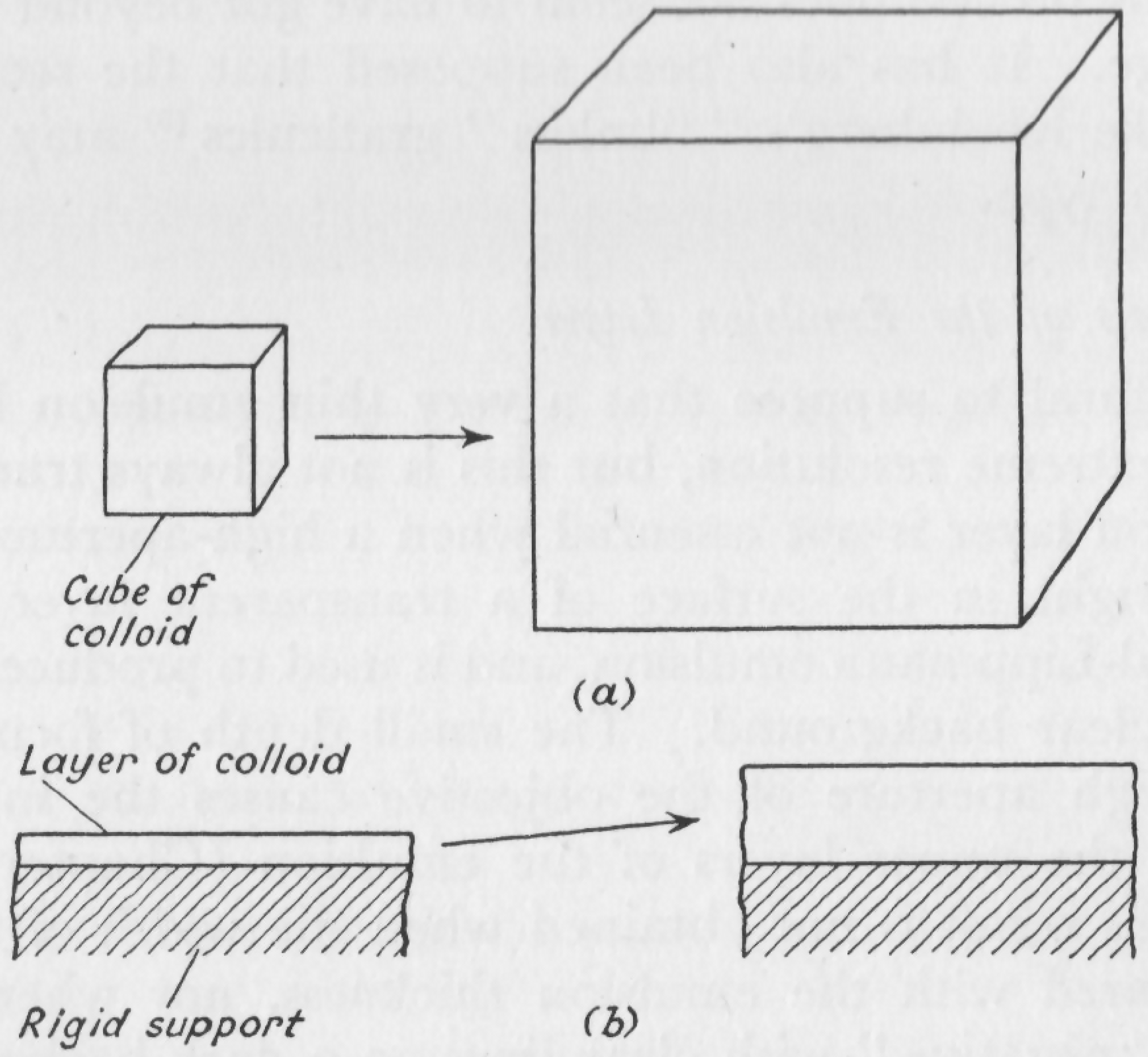


FIG. 11. *Swelling of Colloid Layers.*

(*a*) Cube swells uniformly in all directions.
(*b*) Constraint of coated layer by rigid support only allows vertical swell to occur.

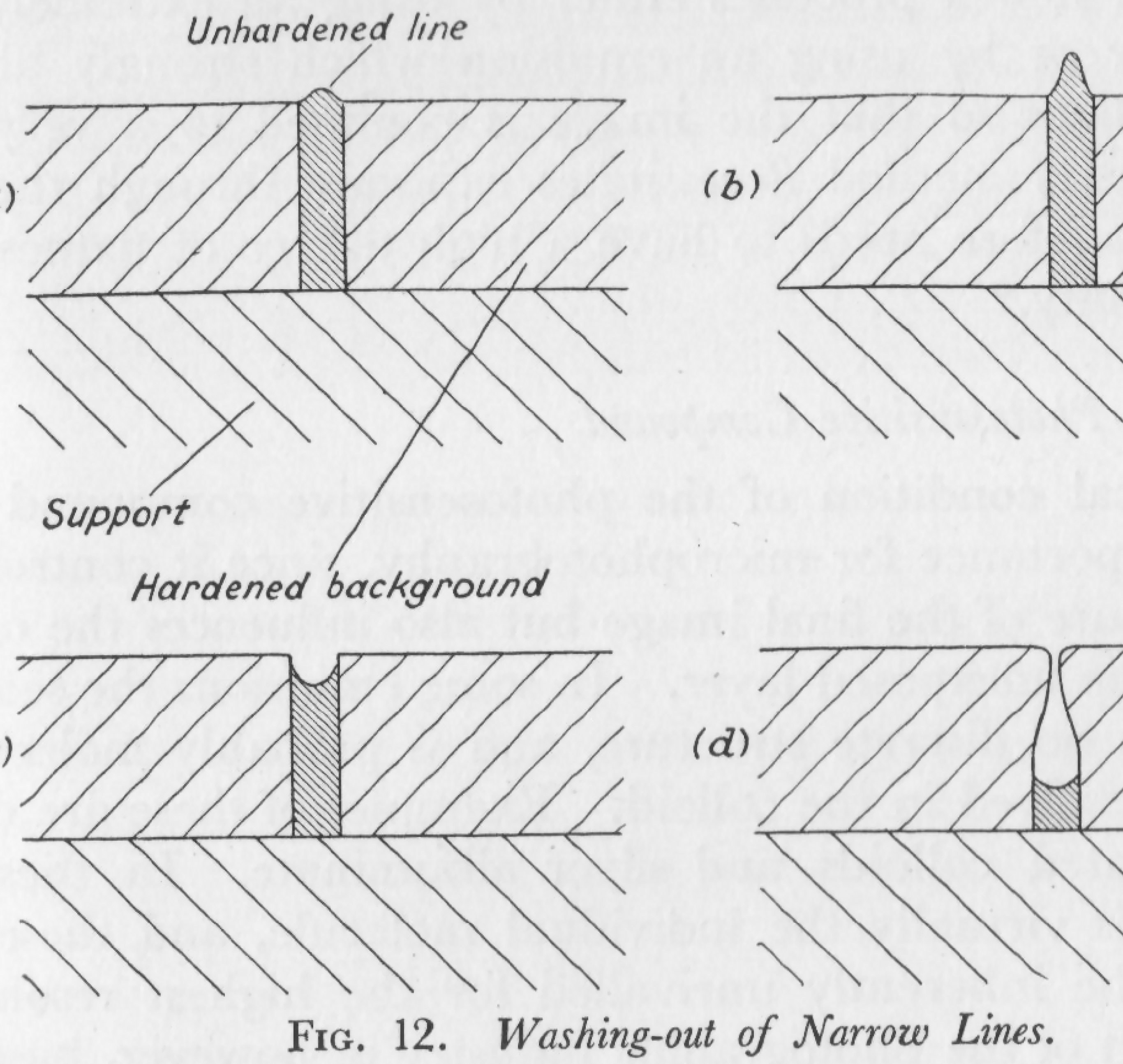


FIG. 12. *Washing-out of Narrow Lines.*

(*a*) At first, unhardened colloid in the lines swells slightly more than background.
(*b*) The difference of swelling increases.
(*c*) Colloid washes from the surface layers of the line.
(*d*) Internal pressure in the hardened (but swollen) colloid causes it to bulge inwards, and hinder further washing-out.

internal stress in the material of the lines is balanced by the stress in the surrounding background, so that the image of the lines is supported by the neighbouring areas and serious distortion cannot occur. When these neighbouring areas are washed away their supporting effect is also removed, and the internal stress in the line can be released by bending of the image. In some cases the lines may fall into sets of waves (*Figure* 13).

These undesirable effects occur mainly when the thickness of the swollen emulsion layer is too great in comparison with the width of the lines. They do not occur when the emulsion is used to produce stencil images with lines whose width is several times the thickness of the swollen layer, and such wide lines are also more likely to resist mechanical damage. Really fine lines can be produced with stencil processes either by using an extremely thin emulsion layer or by using an emulsion which strongly absorbs the exposing light so that the image is confined to a very thin layer. The latter method necessitates exposure through the support, which therefore needs to have a high degree of flatness and optical uniformity.*

Structure of the Photosensitive Compound

The physical condition of the photosensitive compound is of paramount importance for microphotography, since it controls not only the structure of the final image but also influences the optical properties of the unexposed layer. In some emulsions the sensitive compound has no discrete structure, and is probably molecularly dispersed or dissolved in the colloid. Examples of these are diazotype, bichromated colloids and silver albuminate. In these the sensitive unit is virtually the individual molecule, and these processes should be inherently unrivalled for the highest resolution. The major part of the photographic industry is, however, based on the silver-salt emulsions which consist of minute crystals of silver halide embedded in a colloid (usually gelatin). These emulsions behave as if the crystals (or grains) are the photosensitive units, and the grains range in diameter from 0·01 μ up to 2 or 3 μ. Only those in which the majority of the grains are smaller than 0·1 μ are likely to give extreme resolution.

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* Exposure through the support is, however, likely to introduce optical aberrations, and may need the use of a specially-corrected optical system.

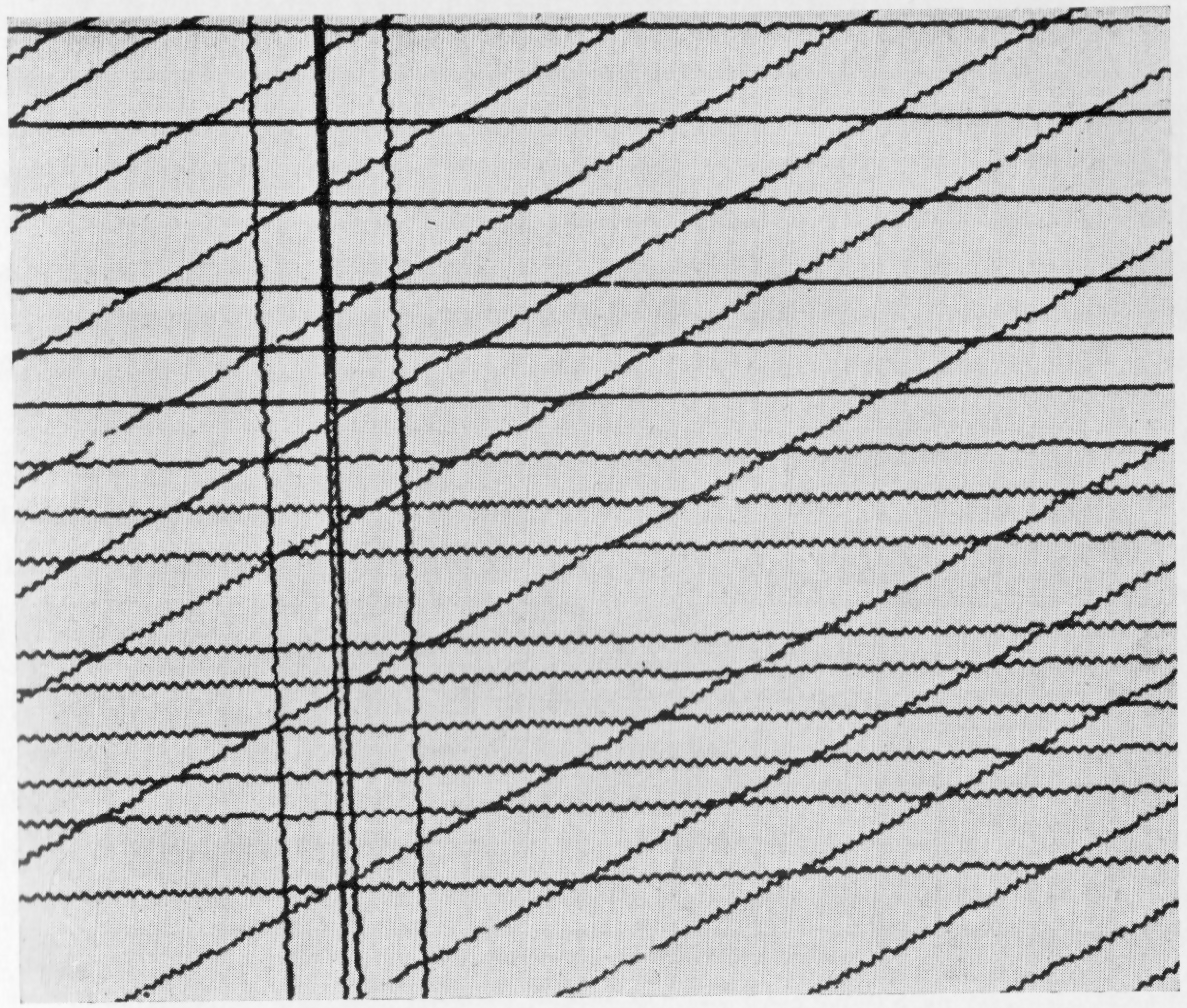


Fig. 13. *Distortion of Fine Lines of Stencil Image.*

Photomicrograph (×23) of image made by developing Maximum Resolution plate to a negative, and washing-out the background with etch-bleach solution. Removal of the support of the gelatin background permitted the straight lines to distort into waves. Note how the thicker lines (at the top) have practically resisted this tendency.

[*Facing p. 28.*

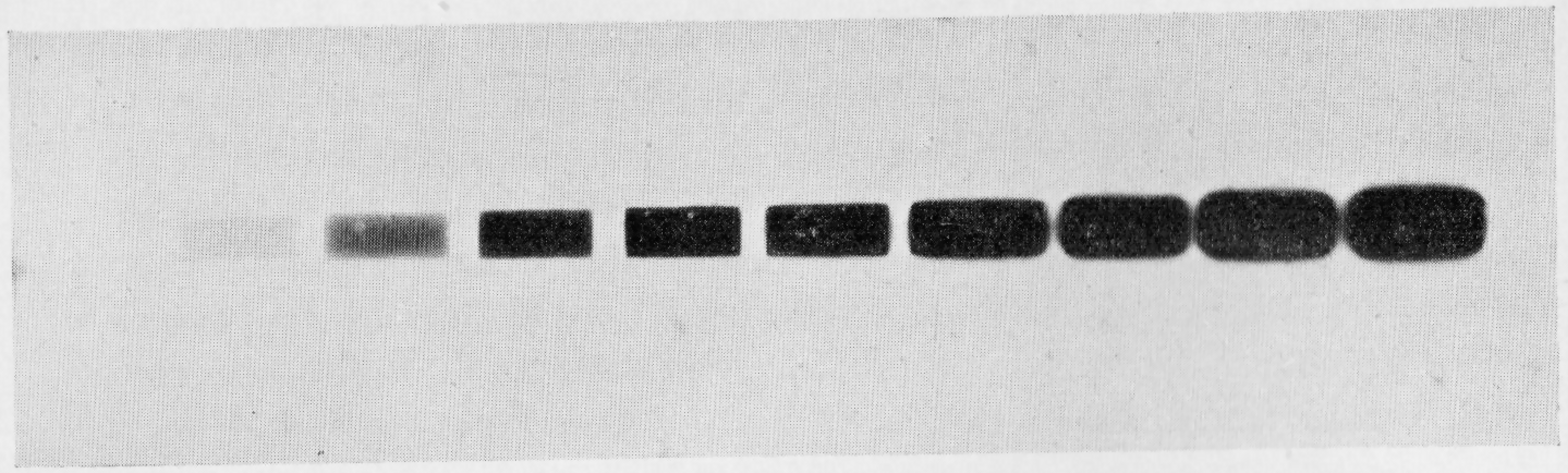


FIG. 15. *"Tadpole" Image on Maximum Resolution Plate.*

Photomicrograph (×125). This image showed that the emulsion was suitable for extreme-resolution work, since the exposure needed to produce adequate density was smaller than that showing serious turbidity (i.e. image spread).

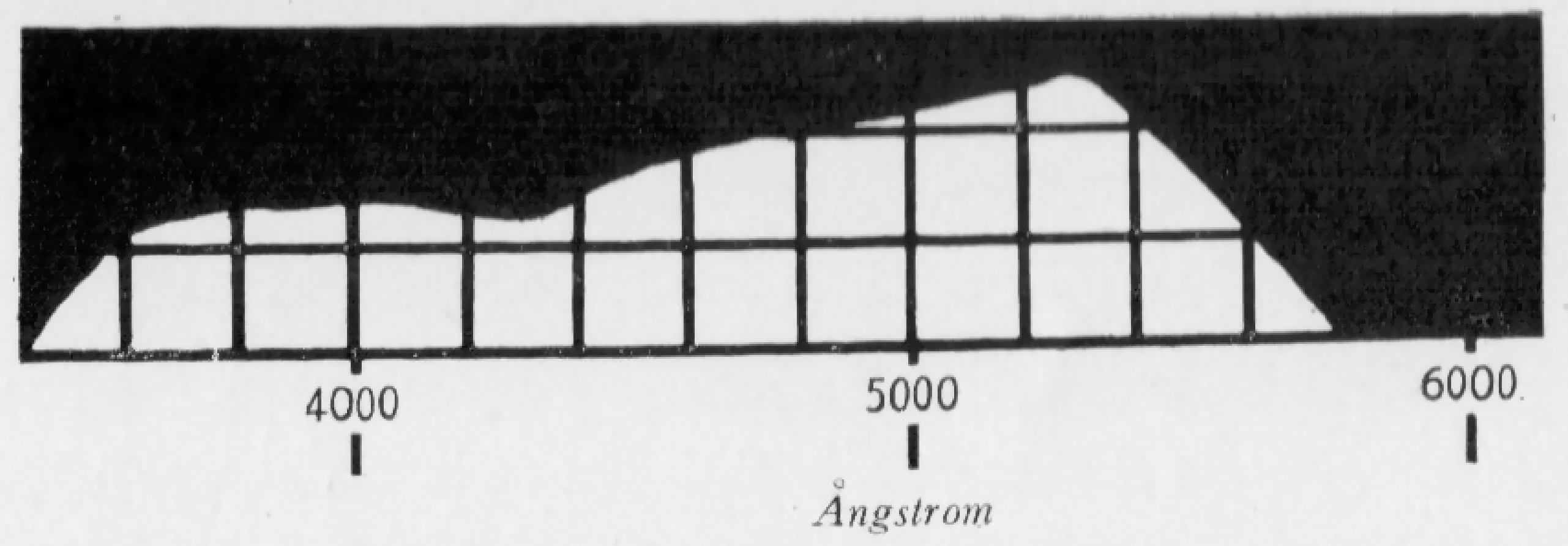
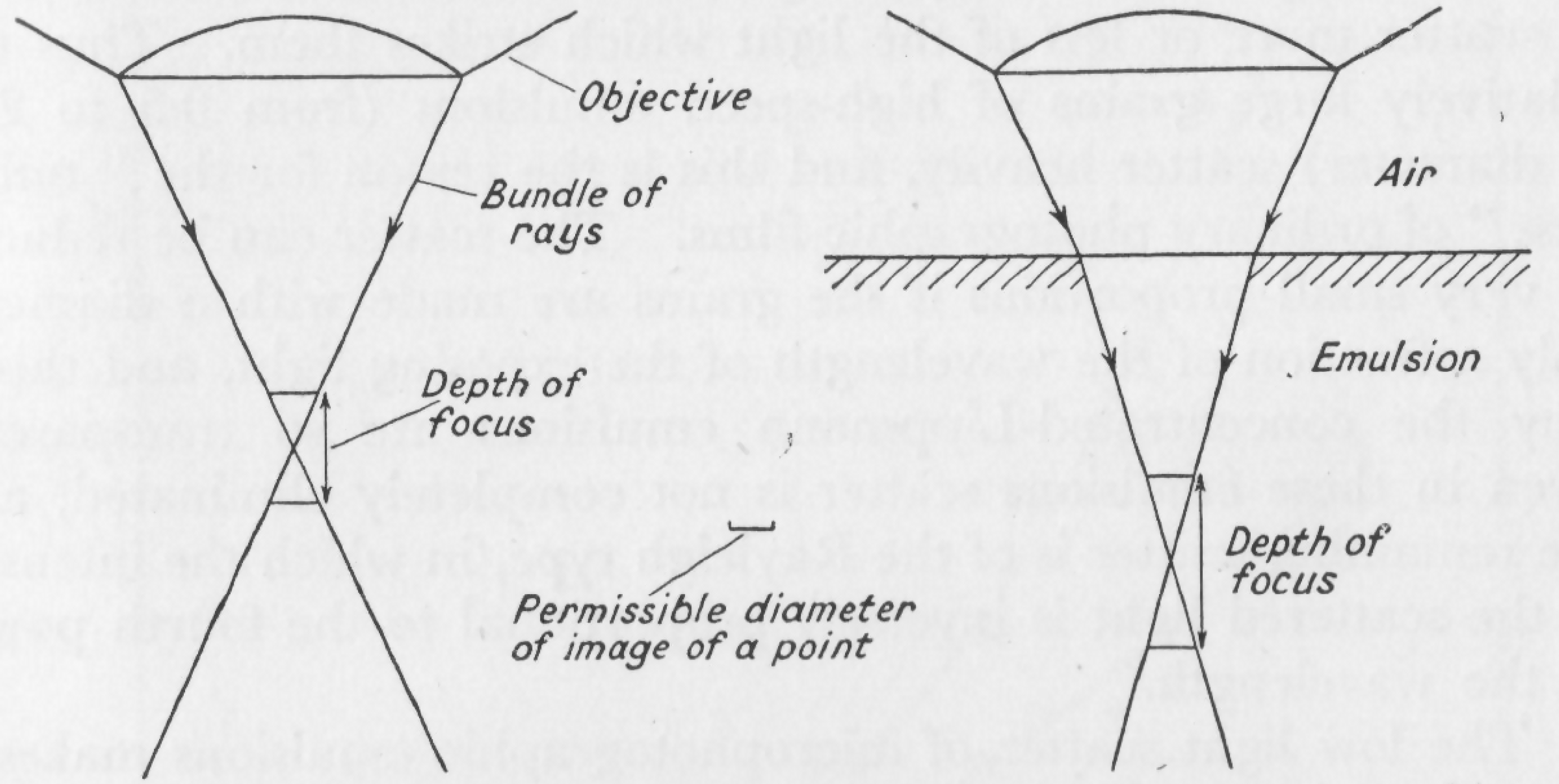


FIG. 17. *Spectral Sensitivity of "Kodak" Maximum Resolution Plate.*
(See p. 33.)

Optical Properties of the Emulsion

The exquisite sharpness required for microphotography can only be obtained by forming an immaculate image *inside* the emulsion layer. The sharp aerial image produced by the objective must not be spoilt by refraction or scatter when the light enters the emulsion. We shall therefore consider how the energy distribution in an aerial image may be modified once the light enters an emulsion.

When light strikes an emulsion it will tend to be refracted at the emulsion/air interface, absorbed in the body of the emulsion, and often also scattered at the surface of the silver-halide grains. The main effect of refraction at the emulsion surface is to reduce the angle of convergence of the bundle of rays forming the image, so that the depth of focus inside the emulsion is actually greater than in air (*Figure* 14). Refraction at a rough emulsion surface will obviously tend to disrupt an image.



(*a*)—*Image formation in air* (*b*)—*Image formation in emulsion*

FIG. 14. *Refraction at the Emulsion Surface.*

The angle of the cone rays from the objective is decreased by refraction, thus increasing the depth of focus *inside* the emulsion layer.

All emulsions useful for extreme-resolution work scatter very little light, and are practically non-turbid for light of wavelengths to which they are normally exposed. The proportion of the incident light absorbed by a given small thickness of the emulsion is independent of the incident intensity, and is practically independent of the position within the emulsion layer. Thus if the first micron thickness halves the intensity, the second will reduce it to one quarter, and so on. The proportion of incident light absorbed by each layer of an emulsion is an important property, since it controls both the depth below the surface at which an image can be formed, as well as the distance which scattered light can travel sideways in the emulsion.

Such materials as the print-out emulsions, wet-collodion and concentrated-Lippmann emulsions have a relatively low absorption : the last material may absorb only 50 per cent. of the incident actinic light in a layer 5 μ thick (Chapter 10). Other emulsions such as bichromated colloids and diazotype absorb more heavily, and Dippel⁽³⁾ showed that the layer produced by impregnating " Cellophane " with the mixture of mercury and diazonium salts absorbed practically all the incident actinic light in the first few microns of the layer.

According to their size, the grains of silver-salt emulsions tend to scatter more or less of the light which strikes them. Thus the relatively large grains of high-speed emulsions (from 0·5 to 2 μ in diameter) scatter heavily, and this is the reason for the " milkiness " of ordinary photographic films. The scatter can be reduced to very small proportions if the grains are made with a diameter only a fraction of the wavelength of the exposing light, and this is why the concentrated-Lippmann emulsions are so transparent. Even in these emulsions scatter is not completely eliminated, and the remaining scatter is of the Rayleigh type, in which the intensity of the scattered light is inversely proportional to the fourth power of the wavelength.

The low light scatter of microphotographic emulsions makes it rather difficult to see which side of the plate is coated with emulsion, but this can be done simply and harmlessly by breathing on the plates. The sides can then be differentiated by the fact that colloid layers such as gelatin or glue prevent the formation of a mist, whereas a mist readily forms on the backing layer or on bare glass.

Interaction of absorption, scatter and the sensitometric properties of an emulsion determines the image spread or *turbidity*. This property can be examined by Mees' " tadpole " test, in which an objective is used to project a reduced image of a slit on the emulsion surface.⁽⁶⁾ An optical step wedge with the steps separated by opaque bands is placed behind the slit, so that the image is divided

into rectangles increasing in brightness from one end to the other. In the absence of turbidity this arrangement should give a series of images of uniform size, and with density increasing with exposure. In fact, increasing exposure usually results in a more or less pronounced widening of the image, and this widening is an indication of the turbidity. Normal silver-halide emulsions are very turbid and thus show pronounced widening at moderate densities, but

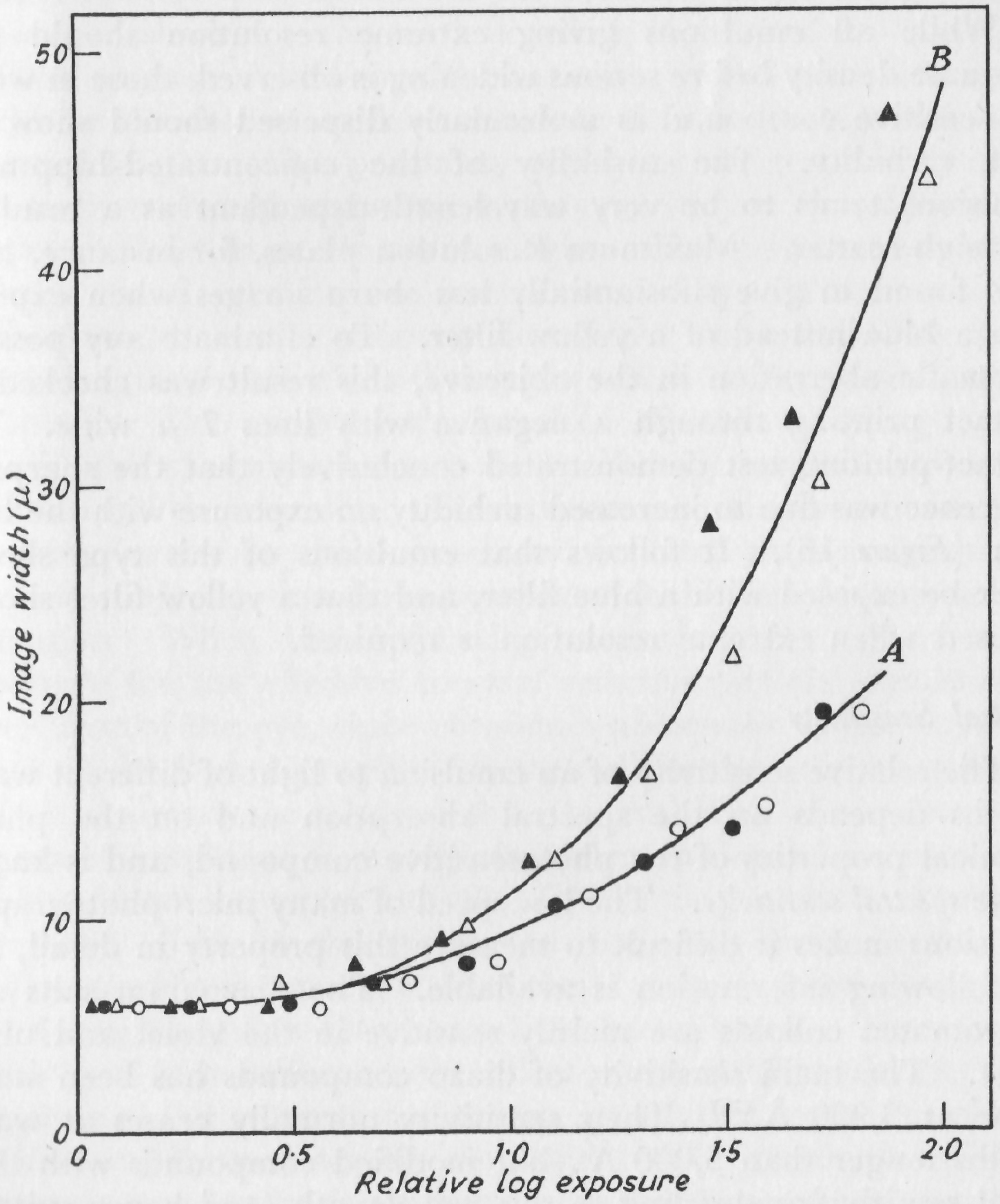


Fig. 16. *Dependence of Turbidity of Maximum Resolution Plates on Wavelength.*

(*a*) ○ ● exposures made with deep yellow filter.
(*b*) △ ▲ with blue filter.
Hollow and solid points represent separate determinations.

microphotographic emulsions suitable for extreme resolution only show serious spread at exposure values greater than those needed to give adequate density (*Figure* 15). This test is a decisive method for determining whether an emulsion is suitable for extreme resolution. It should, however, be pointed out that the aerial image given by an objective is unlikely to be so perfect that no widening at all occurs with sufficient over-exposure, even on a perfectly non-scattering emulsion.

While all emulsions giving extreme resolution should give adequate density before serious widening is observed, those in which the sensitive compound is molecularly dispersed should show the least turbidity. The turbidity of the concentrated-Lippmann emulsions tends to be very wavelength-dependent as a result of Rayleigh scatter. Maximum Resolution plates, for instance, have been found to give substantially less sharp images when exposed with a blue instead of a yellow filter. To eliminate any possible chromatic aberration in the objective, this result was checked by contact printing through a negative with lines 7 μ wide. The contact-printing test demonstrated conclusively that the sharpness difference was due to increased turbidity on exposure with the blue filter (*Figure* 16). It follows that emulsions of this type should never be exposed with a blue filter, and that a yellow filter should be used when extreme resolution is required.

Spectral Sensitivity

The relative sensitivity of an emulsion to light of different wavelengths depends on the spectral absorption and on the photochemical properties of the photosensitive compound, and is known as the *spectral sensitivity.* The low speed of many microphotographic emulsions makes it difficult to measure this property in detail, but the following information is available. The diazonium salts and bichromated colloids are mainly sensitive in the violet and ultra-violet. The main sensitivity of diazo compounds has been stated to be at 3,900 Å.(7a) Their sensitivity normally ceases at wavelengths longer than 5,000 Å., but modified compounds with their useful sensitivity extending to this wavelength (and hence suitable for exposure to tungsten lamps) have been described in patents.(7b) Bichromated colloids have their main sensitivity in the far ultra-violet, but the sensitivity to wavelengths shorter than 3,500 Å. is

not important, because these wavelengths are strongly absorbed by glass.(8) The silver-salt materials are also all sensitive to the ultra-violet, but in addition have useful sensitivity in the violet and blue regions. The higher sensitivity derived from development has allowed their spectral sensitivity to be measured in detail, while sensitizing dyes permit the sensitivity to be extended towards the long-wavelength end of the spectrum (*Figure* 17, facing page 29).

Spectral sensitivity influences the production of extreme resolution in several ways. The resolution limit of a " perfect " objective of given aperture increases with decreasing wavelength, so that it should be possible to make even finer images by exposing with ultra-violet light. This possibility could only be realized by using a specially-corrected objective, together with an emulsion which does not scatter even ultra-violet light. The performance of the objective can depend on the spectral sensitivity of the emulsion in another way, since this property determines the width of the band of wavelengths from a given illuminant which is effective in forming the image. The narrower the band of effective wavelengths, the less will the sharpness tend to be spoiled by residual chromatic aberration of the objective. Some advantage may be obtained by arranging for the emulsion sensitivity to match the wavelength for which an objective has been computed to be free from spherical aberration. When visual focusing methods are used, it is an advantage for the effective spectral sensitivity of the emulsion to match that of the eye, since chromatic aberration of the objective can cause the " photographic " focus to differ from the visual focus.

It has already been noted that the turbidity of concentrated-Lippmann emulsions is strongly wavelength-dependent, and that they should not be exposed to blue light if the maximum sharpness is required. It is for this reason that these emulsions are strongly dye-sensitized to the green, so that they can be exposed to tungsten light through a yellow filter, with little loss of speed. The spectral sensitivity always influences the effective speed of emulsions, since it determines the proportion of the energy emitted by the illuminant which is actually used in image formation. The maximum emission of incandescent lamps, for instance, is in the infra-red and the emission falls off progressively towards shorter wavelengths. Extension of the sensitivity of silver-salt emulsions towards longer wavelengths is an effective method for increasing their speed to this type of source.

Speed

Although relatively low levels of photographic sensitivity or speed can be tolerated when extreme resolution is required, this property is important in determining the convenience of any process. The speed is a complex property depending on many variables, and the influence of spectral sensitivity has just been noted.

In some materials, such as bichromated-colloid, diazotype, dye-bleach and silver-salt " print-out " processes, the final image is built up directly by the light action in units of individual atoms or molecules. The speed of all these processes is low and they only show fairly small differences between each other. In other processes the speed can be increased by using a development step to amplify the mass of the photochemical product. This is frequently done by causing the photochemical product to catalyse metal deposition from a plating bath or " physical developer " (Chapter 4). Amplification factors of many hundreds or thousands can be achieved in this way, so that a high density can be obtained from a quantity of photochemical product so small as to be invisible by itself. This occurs, for instance, in the silver-albuminate process, and the primary photochemical product is known as the *latent image*. It is believed that this type of development can only happen when the latent image consists of nuclei having a minimum critical size. The speed can therefore be increased by allowing the photochemical product to coagulate, and this almost certainly occurs in the Philips' mercury-diazonium process.(3)

The silver-halide-gelatin emulsions provide a more familiar example of the same type of phenomenon. They behave as if the crystals (or grains) are the photosensitive units, and their sensitivity generally increases with the grain size. This is thought to arise in the following way.(9) The action of light at *any* point in a grain causes the eventual deposition of silver as specks at a few preferred places in the grain. As soon as any single speck reaches the minimum critical size, it enables the whole mass of the grain to be converted to silver when the emulsion is treated in a " chemical " developer (Chapter 4). The critical size is thought to be independent of the size of the grain, but the amount of light absorbed by the grain as well as the mass of silver produced on development of each grain both increase with grain size. The photographic

speed of silver-halide emulsions thus increases with grain size. Increasing grain size, unfortunately, inevitably means reduced resolution, so that speed and resolution are intrinsically antagonistic properties. This has been strikingly illustrated by Brock,(10) who plotted the logarithms of the resolution of a number of emulsions against the logarithms of their speeds. With emulsions ranging from " Micro-File " to " Tri-X " the points fell practically on a straight line. The slope of the curve showed that to increase resolution by a given factor, it was necessary to use another emulsion whose speed was reduced by the fourth power of that factor. Thus a sixteen-fold reduction of speed is needed to give about double the resolution. Speed comparisons published by Dippel (3) indicate that this relationship holds approximately even when extended to concentrated-Lippmann emulsions. He found Maximum Resolution plates to be about 10,000 times slower than " Micro-File " panchromatic film. The ratio of the absolute resolution limits of these two emulsions is not much less than ten—the fourth root of 10,000 ! While the significance of this empirical relationship should not be exaggerated, it does show that improved resolution is only likely to be obtained at the expense of a large loss of speed. The importance of this antagonism, moreover, is not restricted to microphotography, but extends to such fields as motion pictures, aerial photography and the operation of " miniature " cameras.

The emulsions which can be used for extreme resolution have different spectral sensitivities, and with some the speed is not constant for all exposure times, but depends on the actual duration of the exposure. This means that a speed comparison may be valid for only one set of exposure conditions. Direct comparisons are, nevertheless, useful for showing the order of speed differences. With tungsten-arc (" Pointolite ") illumination a wet-collodion plate was found to have practically the same speed as a concentrated-Lippmann emulsion, but silver-chloride print-out emulsions in collodion or gelatin were slower by a factor of ten thousand. A bichromated-gelatin layer had a speed slightly less than the print-out emulsions. On exposure to a high-pressure mercury-vapour lamp Dippel (3) found that the mercury-diazonium process gave one-eightieth of the speed of a commercial concentrated-Lippmann emulsion. The difference is likely to have been greater if it had been measured with a tungsten source.

Contrast

The emulsion speed mainly concerns the convenience of a process, but the contrast—or rate of change of blackening with increasing exposure—has a direct effect on the tone reproduction and sharpness of the image. Contrast is usually evaluated from the characteristic curve obtained by giving a graduated series of exposures, measuring the resulting densities, and plotting the densities against the logarithms of the exposures (*Figure* 18). Now one convenient method of giving a graduated series of exposures is to expose the emulsion behind a film bearing a series of uniformly blackened bands (i.e. a *step-wedge*). The relative log(1) exposure behind each band can then be found by subtracting the optical density of each band from an arbitrary constant. A more convenient procedure is to plot the abscissae as step-wedge densities

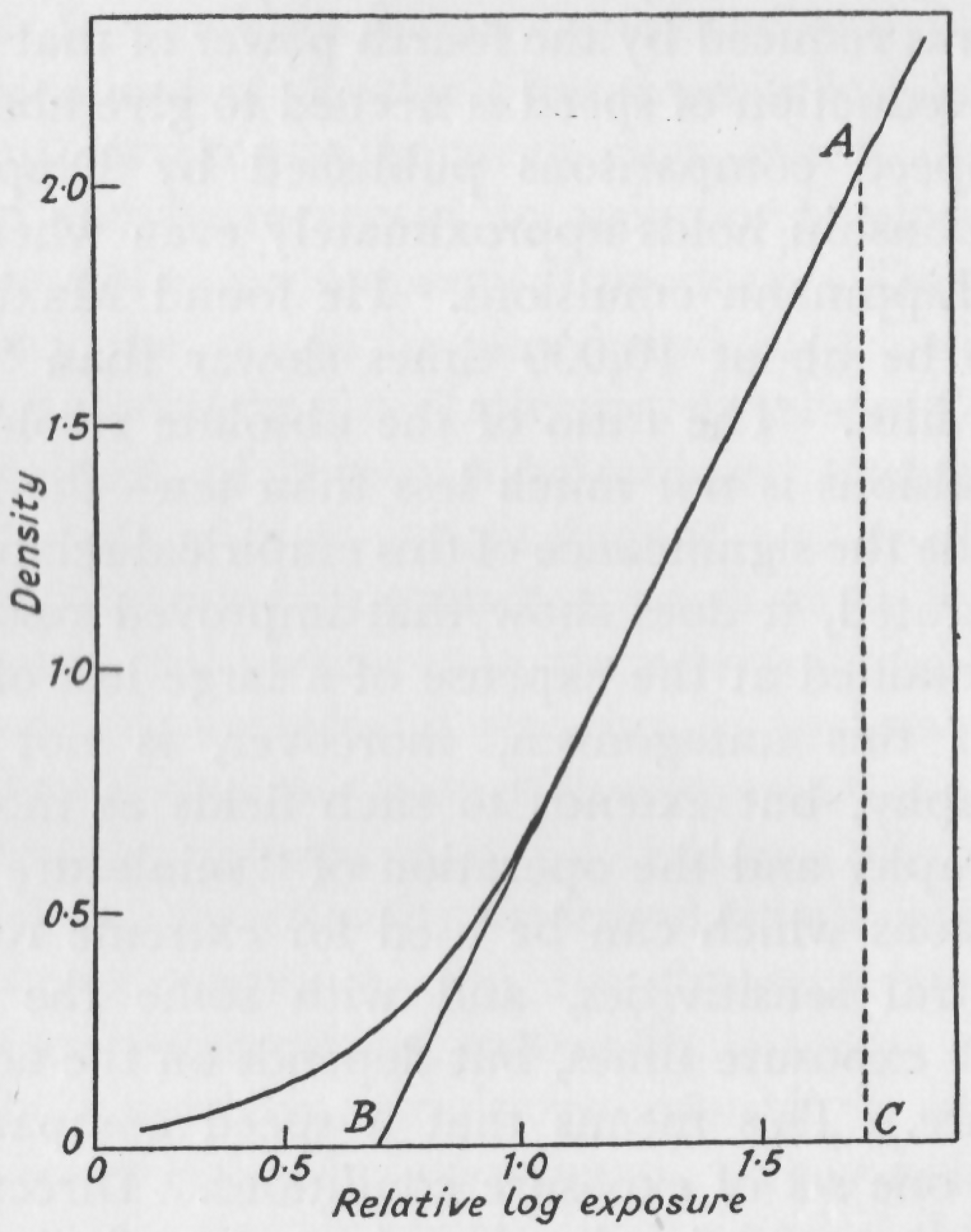


FIG. 18. *Characteristic Curve of Silver-halide Emulsion.*

The contrast is described by the " gamma ", i.e. the slope of the tangent to the straight line $= \frac{AC}{BC}$.

increasing from right to left, and this is equivalent to a scale of exposures increasing from left to right. It therefore follows that the characteristic curve shows how any emulsion will reproduce the tones of a transparency. If the slope of the tangent to the curve (this quantity is known as the *gamma*) is greater than unity the contrast of the image will be increased, and if it is less than unity the contrast will be decreased. In some materials, such as diazotype or the print-out emulsions, the gamma has practically a fixed value close to unity, but in others treated in a metal-forming developer the gamma may depend largely on the composition of the solution and the duration of the development (*Figure* 21).

For practical purposes the factors determining the gamma required are much the same as in other fields of photography. With continuous-tone pictures the gamma should be suited to the density range of the original, and values less than 2 will usually be required. This must be accompanied by an adequate exposure scale, since a low gamma obtained by drastic under-development of a high-contrast emulsion merely results in a poor density range (Chapter 4). Emulsions with higher gammas will normally be used for making line images, and really high values can be beneficial when working close to the resolution limit of the objective. In such cases the aerial image of a line has a flat intensity profile, which can be reproduced as a steep density profile when recorded on a high-contrast emulsion (*Figure* 19). This can result in improved sharpness of the line, and in a reduced line width for any given density. These advantages are obtained at the expense of a decrease in exposure latitude, and the full benefit can only be ensured by accurate exposure control.

The useful contrast range of any one type of extreme-resolution microphotographic emulsion is usually narrow. Contrast is thus an important factor in deciding not only which emulsion, but also what process is needed for any application. This point is well illustrated by the concentrated-Lippmann emulsions. The precipitation conditions needed to ensure extremely fine grain seem to result in an emulsion with very high contrast and small latitude. Restrictions of this type mean that the operator either has to choose a process which suits the density range of the transparency, or else adjust the density range of the transparency to suit an available emulsion. The Philips' mercury-diazonium process provides an exception to this rule, since, as will be seen later in this chapter, the gamma can be changed by adjusting the conditions during the exposure.

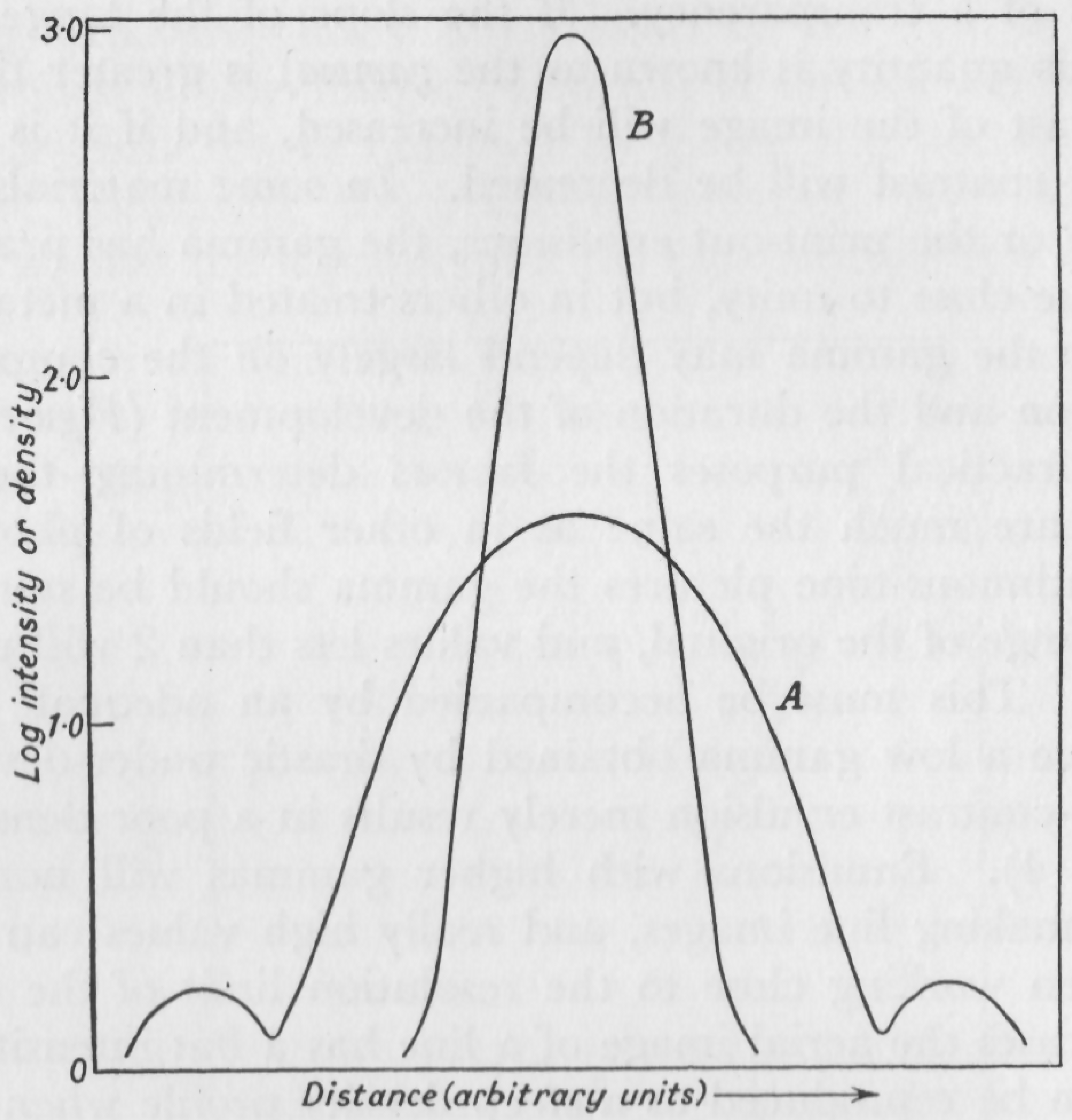


FIG. 19. *Steepening of Line Profile by High-contrast Emulsion.*

Curve (A). Logarithmic intensity profile of line image.
Curve (B). Density profile obtained by recording the same intensities on high-contrast emulsion. (See curve for 2 minutes' development : *Figure 21a.*)

Properties of the Developed Image

Image Structure

Whatever process is used to obtain extreme resolution, the developed image must have a structure which will not hinder the recognition of fine detail. When the image consists of a molecularly dispersed colouring material, its texture will appear quite uniform under the microscope, but satisfactory resolution will only be obtained if the image shows no tendency to " bleed ". Sideways diffusion in the emulsion layer by the photochemical reaction product or by the colouring material formed by development may spoil the sharpness of the image.

The developed image will often consist of small discrete particles of metal dispersed in the colloid layer, and the diameter of these should only be a small proportion of the width of the finest detail it is wished to record. According to the quality required, the minimum ratio of the width of the finest detail to the grain diameter should be five or ten or even twenty to one. In this connection it should be noted that continuous-tone pictures require finer grain than " line " images for a given width of detail. Line images are normally made with a high density and a very steep density gradient at the edge of the line. This means that any granular structure in the body of the line is relatively unobtrusive, or is virtually invisible. In such cases the granular structure of the image can only be seen from the " gritty " appearance of the edge (see *Figure* 8). The density and contrast of most of the detail in continuous-tone pictures will, however, usually be sufficiently low for image structure to be visible in the centre of the image.

The structure of images given by bichromated colloids depends mainly on the mechanical behaviour of the elements of the image during and after the washing-off process. In addition to the phenomena already discussed in connection with the thickness of the emulsion layer, shrinkage effects during drying can cause distortion at the edge of each element of the image.

Light Absorption by the Developed Layer

A further requirement for extreme resolution is that the final image should give the necessary contrast in a very thin layer. This is because the full sharpness of really fine microphotographic images can only be observed by viewing them with high-aperture microscope objectives, having a small depth of focus. This means that only a thin layer of emulsion can be in focus at any one time, and that the image will only show satisfactory sharpness if sufficient density is contained in such a thin layer of the developed emulsion. The image should, ideally, also be confined to this thin layer, since the presence of a perfectly sharp photographic image outside the depth of focus of the viewing microscope will make the image appear less sharp. This is a matter in which the concentrated-Lippmann emulsions score over the old dilute emulsions. The finer grain of the latter should give their images greater sharpness, but much of this advantage is lost by inadequate absorption in the developed layer.

Resolution of the Developed Image

The most important property of a microphotographic emulsion is its ability to reproduce fine details sharply. This has usually been assessed by measuring the *resolving power*, and it has normally been assumed that the resolving power and sharpness of an image are closely correlated properties. Now the resolving power of an emulsion is measured by photographing a test chart containing suitable patterns such as a series of sets of parallel lines of decreasing size. The smallest size at which the component lines of the image can just be separated gives the resolving power, and the numerical figure therefore only indicates the limit of the ability of an emulsion to separate small details. Some caution is needed in interpreting the significance of resolving power figures for photographic emulsions. In the case of microphotographic emulsions the numerical significance of the figures is always doubtful. It is most difficult to devise a testing technique which ensures that the resolution limit of the emulsion is the only factor preventing the achievement of infinite resolution.

The recorded figures, in fact, are likely to depend on the optical equipment used to form the images. Higgins and Jones have drawn attention to another serious difficulty.(11) They approached the subject of image sharpness by considering how this property is appreciated by the eyes. " Sharpness " is essentially a subjective or psycho-physical concept associated with the density gradient across the image of a sharp edge. After considering various criteria they concluded that sharpness correlates best with the mean of the squares of the density gradients across the boundary between a light and a dark image. This mean is computed from microdensitometer traces of the edge of an image, and is proportional to a quantity they term " acutance ". In some cases they found that measurements of the resolving powers of different emulsions gave a misleading impression of their relative image sharpness or acutance values. Photographs reproduced in their paper show that one emulsion having a resolution of 230 lines per millimetre gave a much less sharp image than another emulsion resolving only 130 lines per millimetre.

These difficulties of interpretation do not constitute any objection to resolution tests as such, but rather indicate the danger of an uncritical interpretation of resolution figures. Resolution tests are,

in fact, an excellent method for making comparisons of the microphotographic merits of different emulsions, so long as all are tested on the same equipment. The test images can be used not only to estimate a " maximum " resolving power, but also to determine the quality of reproduction of larger images corresponding to less than the maximum resolution obtainable. These larger images will indicate the sharpness and contrast likely to be obtained in actual microphotographs. They also show how sharpness depends on line width, and hence the narrowest lines which the emulsion will record satisfactorily when exposed with the equipment used for the test. The author has also found that estimation of the resolution obtained under fixed conditions with a 4-mm. ($\frac{1}{6}$-in.) microscope objective was a useful test for the batch control of the quality of concentrated-Lippmann plates. Good correlation was observed between the resolution figure and the image quality obtained with any batch, so long as the emulsion did not scatter strongly. This suggests that the poor correlation described by Higgins and Jones may have been obtained on a fine-grain emulsion, in which considerable light scatter was accompanied by low opacity of the unexposed layer. The fine grain might permit such an emulsion to give a relatively high resolution figure, although the severe image-spread likely to occur with this combination of optical properties would produce an image of poor sharpness.

Subsidiary Emulsion Properties

A number of emulsion properties have no direct influence on the quality of the final microphotographs, but largely control the convenience with which they can be made. Foreign bodies in the emulsion, so small as to be of little consequence for ordinary photographic work, can completely spoil a microphotograph. This can happen when the contaminating particles are no larger than the grains of a high-speed emulsion. Their effect is equally serious whether they are present in the original emulsion or are introduced during coating.

The keeping properties of the coated plates are also important. In the wet-collodion or mercury-diazonium processes, for instance, the layers must be sensitized shortly before use, while layers of bichromated colloids can only be kept a day or two before exposure. Silver-halide-gelatin " dry " plates, by contrast, can be stored in a temperate climate for years. This is not only very convenient, but also assists systematic working with standardized exposures.

The ability to give reproducible results is most desirable, particularly when the exposure latitude is small, or when large numbers of similar images have to be made. It is clear that the quality of the images can only be rigidly controlled with a process capable of giving consistent results. In some processes, for instance with silver-halide dry plates, control for any one batch is achieved simply by adhering to a definite set of exposure and development conditions. In others, such as the wet-collodion process, success cannot be assured by automatically following a prescribed routine, and personal skill is also needed. It is doubtless for this reason that operators at the Möller graticule factory were considered to need at least six months' training.(12)

Emulsions Suitable for Extreme Resolution

We have so far considered emulsion properties in general terms. This approach provides the basic information for deciding how suitable any emulsion is for obtaining extreme resolution, but is no substitute for an examination of individual emulsions. The remainder of this chapter will therefore be devoted to a review of the more notable processes which can be used.

Silver-Halide-Gelatin Emulsions

The advantages which permitted silver-halide-gelatin " dry " plate emulsions to displace earlier photographic materials for general photography, should also appeal to most workers in microphotography. We have already noted that emulsions for extreme resolution must have grain diameters of less than 0·1 μ, and this automatically eliminates the vast majority of commercial dry-plate emulsions. Probably the first silver-halide-gelatin emulsions with an average grain size below this limit were made for the Lippmann interference process of colour photography (Chapter 13). The successful operation of this process involved the production of images of interference fringes at a frequency of 6,000 lines per millimetre (page 290).

Lippmann emulsions are made by using exceptionally dilute solutions of salts and silver nitrate, and by precipitating the silver halide in the presence of a high concentration of gelatin.(13) Both these conditions favour the production of very fine grain. The emulsion is coated immediately after precipitation and washed as soon as the layer has set: a procedure giving the least possible opportunity for grain growth to occur. Emulsions made in this way have a very low silver-halide/gelatin ratio, so that only low densities (0·5 or less) are obtained by chemical development of coatings having a normal thickness for dry-plate emulsions. The extreme fineness of grain, however, means that the image consists of a vast multitude of minute silver particles, which serve as excellent nuclei for physical intensification. Very high densities can thus be obtained by physical intensification (*Figure* 20), or by developing directly in a physical developer.

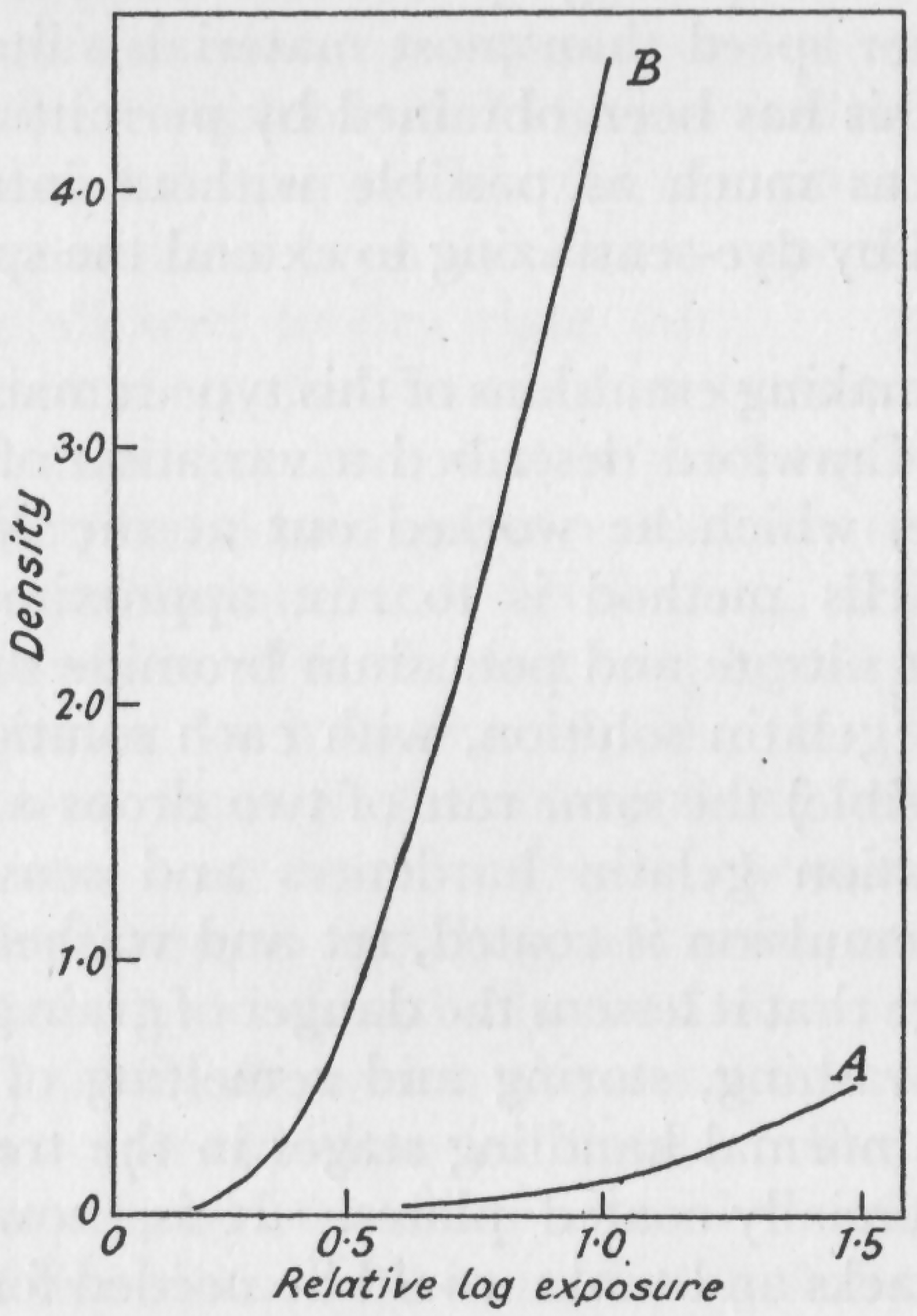


FIG. 20. *Physical Intensification of Lippmann Plate.*

(*A*) Curve produced by chemical development. 3 minutes at 70° F. in D.158.
(*B*) Intensified image resulting from physical intensification of developed image.

In 1940 methods were discovered for increasing the silver content of Lippmann emulsions without unduly increasing their grain size,(14a) and several manufacturers now produce plates which give densities of three or more by direct chemical development, accompanied by a resolution of over 1,000 lines/mm. and a speed that is not impracticably low for many purposes. Materials of this type are the Eastman Kodak High Resolution and Spectroscopic 649 G. H. plates,(14b) the Agfa Lippmann plate (14c) and the " Maximum Resolution " plate made by Kodak Ltd. in Great Britain. The emulsions used on all these materials are conveniently described as concentrated-Lippmann emulsions. The fact that sufficient density can be obtained by direct chemical development means that the results can be methodically controlled by time and temperature, and the images need not be watched during development. This property makes these materials suitable for the production of large batches of microphotographs. The emulsions in this group also have a higher speed than most materials suitable for extreme resolution, and this has been obtained by permitting the grain size to be increased as much as possible without introducing serious light scatter, and by dye-sensitizing to extend the spectral sensitivity into the green.

Methods for making emulsions of this type remained an industrial " secret ", until Crawford described a variation of the early Lippmann procedure, which he worked out at the National Physical Laboratory.(15) His method is to run approximately equivalent solutions of silver nitrate and potassium bromide drop by drop into a rapidly-stirred gelatin solution, with each solution running in at (as nearly as possible) the same rate of two drops a second. At the end of precipitation gelatin hardeners and sensitizing dyes are added, and the emulsion is coated, set and washed. This method has the advantage that it lessens the danger of grain growth occurring during setting, washing, storing and remelting of bulk emulsion ; which constitute normal handling stages in the treatment of emulsions for commercially-coated plates. It is, however, clear that quite elaborate racks and tanks would be needed for washing coated plates in the number and variety of sizes needed for production coatings of an economically reasonable number of plates. Care is also obviously needed to prevent the washing from depositing dirt on the emulsion surface before it is even exposed. On the other hand, Crawford's method is certainly attractive for a microphotographer requiring a few plates for his own use.

The Wet-Collodion Process

The wet-collodion process has been used for making microphotographs ever since its invention by Scott Archer in 1852. It enabled Dancer to perform his pioneering experiments, and Dagron used a variation for the operation of the Paris Pigeon Post in 1870–71 (Chapter 12, page 233). It is, in fact, still used for the large-scale production of graticules at the Möller factory.(12)

In essentials the process consists of the following steps. After cleaning the glass, and applying a " sub " coating to secure adhesion, the operator coats the glass by flowing over a collodion solution containing soluble iodides. As soon as sufficient solvent has evaporated to let the layer set, the plate is sensitized by bathing in a silver-nitrate solution containing dissolved silver iodide. This results in the precipitation of a fine-grain deposit of silver iodide in the layer, and the plate is exposed and developed before the emulsion can dry completely. This procedure ensures that the layer is still sufficiently permeable for the processing solutions to penetrate : the emulsion layer becomes impermeable to aqueous solutions if it is allowed to dry right out.

It is important to realize that the wet-collodion " process " is not one standardized method, but a whole group of procedures among which may be found great variations in the composition of the sensitizing solutions and developing methods. The form most widely known in 1956 is that employed in making photomechanical negatives for half-tone blocks ; but the methods used by photo-engravers often give a coarse developed grain, which is useless for extreme resolution. Precise working details of the methods used by Dancer and Dagron never seem to have been published. It is believed that the latter used a variation originated by Taupenot in 1855, in which the sensitized collodion plate is covered with an iodized-albumen layer. The resultant almost insensitive plates can be stored for several months, and the plates are re-sensitized in a silver bath immediately before exposure. The reader wishing to operate a collodion process is advised to consult published accounts of methods which have been specifically worked out for extreme resolution. Even these differ amongst themselves. Lehmann and Miethe, for instance, used the Taupenot process, and developed the plates first in a mercury and then in a silver physical developer.(16) In another variation of this process used by the firm of Zeiss for making graticules, all the constituent solutions were different from those used by Lehmann and Miethe, and a silver physical developer containing pyrogallol was used.(17) The Möller factory employed still another procedure of the type introduced by Russell in 1861 ; in which the sensitized plates are treated with tannin before exposure, and this is stated to act both as a sensitizer and anti-foggant.

In addition to the employment of appropriate solutions and a suitable variety of collodion, the success of the wet-collodion process depends on the skill and experience of the operator. There seems to be little question of being able to obtain the desired result immediately by rigorously following a prescribed drill. This is the reason why photo-engraving wet-plate operators require considerable training, and why the firm of Möller insist on plates being exposed and processed by the operator who sensitized them. The reader would, therefore, seem to be well advised not to use this process unless he is prepared to devote the time needed to acquire the art.

In spite of these disadvantages the wet-collodion process has many attractive points. The effective speed is comparable with that of the concentrated-Lippmann emulsions, and changes in the development procedures can be used to give the high contrast needed for line images, or the low contrast required for continuous-tone pictures. The fact that the entire process from coating the emulsion to producing the images can be completed in about 30 minutes in a single room is an attractive feature, in addition to the ease with which glass blanks of any size or shape can be sensitized. An outstanding advantage of the procedure operated at the Möller factory is the ability to remove individual images from the original plate on which many are made, and transfer them without distortion to the final graticule blanks. It must be for reasons such as this that the firm has used wet collodion as a large-scale production method for many years.

Silver-Salt " Print-Out " Processes

All processes giving a silver image have the advantage that the image is stable to light, while its resistance to chemical attack can be readily increased by conversion to gold or platinum. With processes using a development stage, however, there is always a danger that the image structure may become coarsened. Goldberg (1) avoided this by employing a collodion layer containing silver chloride and citric acid. The citric acid reacts with the chlorine produced by photolysis, and the layer can thus be " printed-out " by a heavy exposure to give satisfactory contrast and density without development. Three stock collodion solutions containing respectively silver nitrate, lithium chloride and citric acid are required for this process. These keep indefinitely if tightly stoppered, and the emulsion is made by mixing them shortly before coating. After coating, the plates are exposed until sufficient density is obtained, and the image is fixed and gold toned. The fact that the image becomes directly visible simplifies exposure control, and Goldberg interrupted his exposure at intervals, so that the density could be judged on examination by non-actinic light (Chapter 6). In addition the low speed of the emulsion allows it to be handled by ordinary tungsten illumination, but condenser illumination in the camera is needed to ensure tolerably brief exposures.

With this process Goldberg produced images whose fineness has been a challenge to all subsequent workers. He made legible copies of a page of 50 lines of print reduced to a height of 0·004 in. (0·1 mm.) so that individual letters were only one micron (0·00004 in.) high.(1)

Silver-chloride print-out emulsions in gelatin have also been used for extreme resolution,(18) but are now of little more than historical interest.

The Silver-Albumen Process

The use of a silver-sensitized albumen layer for making contact copies from mechanically-ruled scales has been described by Burmistrov.(19) An exceedingly thin layer of egg albumen (0·5 microns thick) was coated on plates by whirling, and after drying was sensitized in a 5 per cent. silver-nitrate solution. The excess silver salts were washed out in running water. After drying, the plates were exposed behind a master negative for 20 minutes at 3 ft. from a 20-ampere arc, and were developed in a physical developer. The sensitive compound probably consists of molecularly dispersed " silver-albuminate ", and there is every reason to suppose that this material would give extreme resolution.

Processes using Photosensitive Organic Compounds

Many dyes are unstable to light, and chemists have considered the use of such compounds for photography, and in particular for the copying of colour photographs.(20) In some of these processes an addition agent is used to increase the light-sensitivity of the dye, and it is desirable that the removal of the addition agent should leave a reasonably stable dye image. The optical properties of a colloid layer impregnated with such a dye would be admirably suited for making minute images. An important additional requirement is that the un-decomposed dye should not diffuse after exposure. While this type of process is of little immediate practical interest, dye-bleach processes using several dyes appear to offer the best hope for the production of multi-coloured images of truly microscopic proportions.

Processes employing diazonium salts are of greater interest since they are already widely used in the photographic copying of plans and drawings. The diazo compound absorbs in the ultra-violet and blue, and is decomposed directly on absorption of light. The image so formed generally only has a pale yellow colour and gives poor visual contrast, but can be developed in several ways.

(i) The un-decomposed diazonium salt can be converted to a deeply-coloured dye by coupling with a suitable phenol, and this gives a direct-positive image in which the *unexposed* areas are heavily coloured.

(ii) The decomposition product (usually a phenol) can be coupled with another diazonium salt to form a dye image heavily coloured in the *exposed* areas.

(iii) The decomposition product can be allowed to react with a metal salt (usually mercury), resulting in the formation of nuclei for physical development.

Philips' Mercury-Diazonium Process

The third of these methods is of great interest for extreme resolution.(3) As with other diazo processes, absorbent supports are simply sensitized by allowing them to soak up a solution of the diazonium salt, which in this case also contains a mercurous salt. " Cellophane " is a cheap and suitable support, which gives the necessary clarity and smooth surface. On exposure the decomposition product of the diazonium salt can react either with the mercurous salt or with residual un-decomposed diazonium salt. The proportions of the decomposition product reacting in either of these ways depends on the moisture content of the layer at the instant of exposure and on the light intensity of the exposure. The fate of this product influences the contrast, and high intensities and low humidities favour high contrast and low intensities and high humidities favour low contrast. The possibility of varying the contrast in this way is obviously useful for changing the quality of the tone reproduction, but it also means that satisfactory operation of the process depends on adequate control of the humidity of the layer. The formation of a final image consisting of metal stabilizes the image against fading or diffusion of the image substance. In addition the use of physical development raises the photographic sensitivity of this process substantially above the level of ordinary diazo processes.

The mercury-diazonium process does not yet appear to have been exploited commercially, but many of its features have been protected by patents.* It has been suggested as a cheap method for making document records, and for recording music in the form of sound-tracks scanned by photo-electric reproducers. The extreme resolution of the emulsion should permit the dimensions of the sound-track to be greatly reduced, so that the records should have some of the attributes of long-playing and slow-running disc records.

Bichromated Colloids

When thin layers of glue, gelatin or some other colloids containing a dichromate are exposed to blue or ultra-violet light, the dichromate is reduced, and the resultant products combine with the colloid and make it insoluble. Treatment with a solvent removes the unexposed parts of the layer, and leaves the exposed and " hardened " or " tanned " areas in the form of a stencil image. The connection between the coating thickness and resolution of such layers has already been discussed earlier in this chapter.

Layers of bichromated glue thin enough to be used for making stage micrometers can be produced by applying the solution to the centre of the plate, and removing the excess by rotating rapidly on a " whirler ". In order to obtain extreme resolution, layers produced in this way should be well under one micron thick, and should show strong interference colours. The photographic speed is low, and contact-printing exposures of the order of minutes are required at a few feet from a carbon or mercury arc. With such a thin layer of colloid the relief image itself is so transparent as to be almost invisible, but can be blackened in various ways. Opaque lead-sulphide deposits can be obtained by alternately bathing in a solution of a lead salt and in a solution of sodium sulphide until sufficient density is obtained. The colloid can also be coated with nuclei for physical development already incorporated.

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* It is, in this connection, interesting to note that the rights to some of the American patents (U.S. patents 2,571,670 and 2,571,671) have been assigned to the Hartford National Bank and Trust Company.

The bichromated colloid processes are now mainly of interest as the first stage in the elaborate procedures used for making graticules (Chapter 11). Relief images made by special processing methods from silver-halide emulsions can also be used for the same purpose (Chapter 4).

Phenol-formaldehyde Resins Sensitized with Iodoform

The production of photographic stencils resistant to hydrofluoric acid is an important problem for the production of etched-glass graticules (Chapter 11), and most processes hitherto published have required the application of multiple coatings to the glass in order to secure the necessary resistance to etching. Davis and Pope of the United States National Bureau of Standards have now published details of a method for producing a satisfactory photographic stencil from a single coating.(21)

For this purpose they used a partly-polymerized mixture of phenol-formaldehyde and resorcinol-formaldehyde resins, which was sensitized by the addition of iodoform. On exposure to violet and ultra-violet light, the resins were insolubilized by further polymerization, probably as a consequence of photochemical oxidation of the iodoform. The unexposed areas were washed out with a special solvent mixture, and simple baking then gave the stencil adequate resistance to hydrofluoric acid, which was used to etch the glass.

In addition to the sensitized system itself, the coating method used is also of interest. They coated the glass blanks by immersing them in the sensitizing solution in an accumulator jar, and then pulling them very steadily out through the surface of the solution. With this method the coating thickness can be controlled with considerable precision, since it depends on the viscosity and specific gravity of the solution and on the rate of withdrawal. Under their conditions a withdrawal rate of 1 in. (2·5 cm.) in 6¾ seconds was found to give a dried-down layer of thickness 0·000038 in. (0·95 μ). Photomicrographs indicated that duplicate divided circles made by this process were of high quality.

Photosensitive Glass

Processes recently developed for making photographic images directly in glass are also of potential interest for extreme resolution. These have been originated by the Corning Glass Company, and in the first form used a glass which became strongly coloured on heating to just below the softening point after exposure to ultra-violet light.(22) While such a process should intrinsically be capable of high resolution, published accounts suggest that the layer needed to give adequate density might be undesirably thick for extreme resolution. A second process developed by the same company is of even greater interest, since the exposure and heat treatment accelerated etching by hydrofluoric acid instead of producing a colour.(23) It has been stated that the exposed areas etch fifty times more rapidly than the unexposed. This means that the etching can faithfully follow the path of the exposing light into or even through the glass, with practically no undercutting. With suitable illumination intense contrast can be obtained from quite a shallow etch, and etched lines can also be filled with pigment. This remarkable process should thus be more suitable for extreme resolution, and could have a great influence on the production of instrument scales.

Selection of a Sensitive Material

It is apparent that the reader wishing to obtain extreme resolution can choose from a great variety of processes. This chapter has attempted to present the main facts needed for making a choice, and will conclude with some suggestions for restricting the number the reader need seriously consider. The choice can be conveniently divided into several stages.

(i) Some of the properties needed in the sensitive material can be stipulated by considering the required final result. This consideration must embrace not only properties controlling image quality, but also such secondary properties as convenience of coating the emulsion on the support, the suitability of the image for special applications and the dimensional and chemical stability required of the image.

(ii) The suitability of the processes chosen in stage (i) for use with available equipment may next be examined, particularly with respect to their use with specific focusing mechanisms, objectives and illuminants.

(iii) The final selection can then be based on convenience and cost. Convenience includes many factors such as availability, keeping properties, reproducibility, preparations required before exposure, the amount of training and practice needed, and the suitability of the process for the numbers of images it is proposed to make.

Compromises may often have to be made, and personal preferences can easily lead to different decisions at various times. The beginner is often likely to choose one of the commercially-available concentrated-Lippmann plates, so that practice in the art of microphotography can be started with a minimum of delay. The choice for commercial operators may be influenced by the numbers of images required. Those producing very large numbers of images might consider it worth while to install the equipment and train the staff needed for the wet-collodion process. The amateur is, of course, free to follow his own inclination entirely. Some might wish to try several processes, while others could experiment with new processes. One fascinating field which is virtually untouched is the possibility of producing microphotographs in colour. This is a task to challenge the skill of the most ambitious worker.

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CHAPTER 4

The Processing of Microphotographs

ALL PHOTOGRAPHIC MATERIALS require chemical treatment after exposure, either to make the image permanent or to increase the blackness, or even to make the image visible at all. The appearance of ordinary photographs can be modified by adjusting the processing conditions, but the quality of microphotographs tends to be exceptionally sensitive to changes in processing. The precise conditions may influence :

the microscopical structure of the image,
the effective emulsion speed,
lateral spread of the image or movement of the layer,
the cleanliness of the final pictures.

The ways in which these properties are influenced depend on the nature of the emulsion and processing operations. The interaction of these factors is the main subject of this chapter, which is largely concerned with extreme-resolution microphotography. Processing of commercial document microphotographs, which are often on long lengths of film, is discussed separately in Chapter 12.

Classification of Processing Operations

Processing operations can be divided into a few main types. *Development* is a general term applied to treatments which increase the visibility of the image in an exposed emulsion : often it signifies the production of a visible picture from an invisible (latent) image. *Fixation* consists in the removal or modification of the residue of the light-sensitive substance, so that the image is stabilized against further light action. Images in silver-salt emulsions may also be subjected to after-treatments to decrease or increase the blackening (*reduction* or *intensification*), or to modify the image colour (*toning*). The processed images also have to be washed to remove harmful constituents of the processing solutions, and finally have to be dried to reduce the risk of mechanical damage.

Development

In Chapter 3 the reader will have noticed that some emulsions (notably the " print-out " and dye-bleach materials) require no development at all, whereas the development of other materials can take a variety of forms.

Development of Diazotype Layers

The development of most diazotype materials consists in the conversion of a colourless or pale-coloured organic compound to give a strongly-coloured dye. In this conversion one molecule of dye is formed from each molecule of diazonium salt (direct-positive image) or breakdown product (negative image). There is thus no multiplication of the number of molecules forming the image, and development amounts merely to the shifting of the absorption band of the image from the violet or ultra-violet into the visible region of the spectrum. In the Philips' mercury-diazonium process,(1) however, the photochemical image consists of minute droplets of mercury and these are developed by the process of physical development which is described later.

Development of Bichromated Colloids

The development of bichromated colloids usually occurs in two stages. The first is the " washing-out " process whereby the unexposed and still-soluble areas of the layer are dissolved by a solvent which cannot attack the hardened exposed parts. The solvent may be cold or hot water, or an organic solvent, according to the solubility of the colloid constituting the layer. When bichromated colloids are used for microphotography they have to be coated so thinly that the washed-out stencil is practically invisible (Chapter 3), and in this form it is useless. Further processes are therefore needed to darken it by dyeing, or by bathing it alternately in a solution of a lead salt and of sodium sulphide, so that a dense deposit of lead sulphide is built up.(2) In some cases nuclei for physical development are added to the colloid before coating, so that the washed-out stencil can conveniently be blackened by physical development. Washed-out stencil images can also be made visible by using them as a physical barrier against the deposition of fresh material on the support, or against the etching of the support itself or of a special under-layer. Such processes are used in the making of graticules. (See Chapter 11.)

Processing by " wash-off " methods is potentially capable of giving exceptionally clean images, since the colloid is completely removed from the non-image areas, together with its own population of dirt particles. Stencil images can also be obtained by special treatments of silver-halide dry-plate emulsions, but the resolution of the stencils is likely to be inferior to those obtained from the much thinner layers of bichromated colloids.

Physical Development of Metallic Nuclei

The exposure of silver-salt emulsions and of mercury-diazonium layers is believed to cause the deposition of minute particles of metal (see Chapter 3). These may remain in the layer after all the photosensitive compound has been removed by washing or by fixing in a suitable solvent ; but they can still act as centres for the deposition of silver or mercury from special plating baths. It was at one time thought that the mechanism of this type of development was simply physical condensation, such as occurs in a cloud, and the process was therefore called " physical " development. The present view is that it is caused by heterogeneous catalysis,(3) but the original name is still used.

Physical developers resemble mirror-coating solutions in that they both contain a metal salt *and* a reducing agent ; but the conditions in physical developers are adjusted so that deposition from the solution is slow in the absence of an external stimulus. Deposition is accelerated when the solution comes into contact with metal nuclei, and the consequent growth of the nuclei makes the image visible. If carried too far, this growth can also produce coarsening of the visible image structure, and it is interesting to note that prevention of this defect was discussed in the literature before 1860.

For our purpose it is important to note that most of the metal in the developed image comes from the solution, so that there is no automatic proportionality between the total mass of the exposed grains and the eventual mass of the developed image. Changes in the degree of development can thus lead to exceptionally large variations in the contrast and density of the image.

Physical development demands considerable care. Since both components of the reacting system are present in the solution from the start (see Appendix I, A), the reaction between the metal ions and the reducing agent may be brought about by influences other than latent-image nuclei in an exposed emulsion. Such actions can cause silver deposition to occur on the walls of measuring vessels and dishes or in the bulk of the solution, and this leads to a premature loss of development activity. Scrupulous cleanliness should be observed in the handling of all solutions, and cleaning of glass vessels with nitric-acid or chromic-acid cleaners is recommended.* The development should be carried out in an unmarked porcelain (or even better in a glass) dish. Dirt held in the cracks of old porcelain dishes is likely to cause trouble. Further useful precautions are to prepare the metal-containing solution in a dim light, and filter both solutions into clean bottles after being allowed to settle over-night. The metal-containing solution should also be stored in a brown bottle. The tendency for the complete solution to exhaust itself can be discouraged by adding a protective colloid such as gelatin or gum arabic, and by mixing the two solutions *immediately* before starting to develop each plate.

Some emulsions such as wet-collodion and silver-albuminate have always been developed in a physical developer, but the process has hitherto been so uncertain that it has demanded control of development by inspection. A number of ways of overcoming this difficulty have been patented by chemists of the Philips' Research Laboratories.(4) These include the use of a solution which takes many hours to develop at room temperature, and is hence also relatively stable.(5) The exposed emulsion is impregnated with this solution by bathing and is then developed in a minute or less by heating to 140° F. (60° C.). The procedure also ensures that only enough solution for the development of the image is taken up by the emulsion, and this could lead to considerable economies. Physical developers can be used to intensify chemically-developed microphotographic images, and the method is discussed later in this chapter.

Chemical Development of " Dry-plate " Emulsions

The minute crystals (grains) of silver-halide-gelatin emulsions react only slowly when the unexposed emulsion is bathed in suitable solutions of a reducing agent. Grains on which traces of silver have been formed by exposure are, however, rapidly and completely reduced to silver. This process is known as *chemical development*, and is distinguished from physical development by the fact that all the metal in the developed grains is provided by the exposed grains themselves, rather than by the solution.

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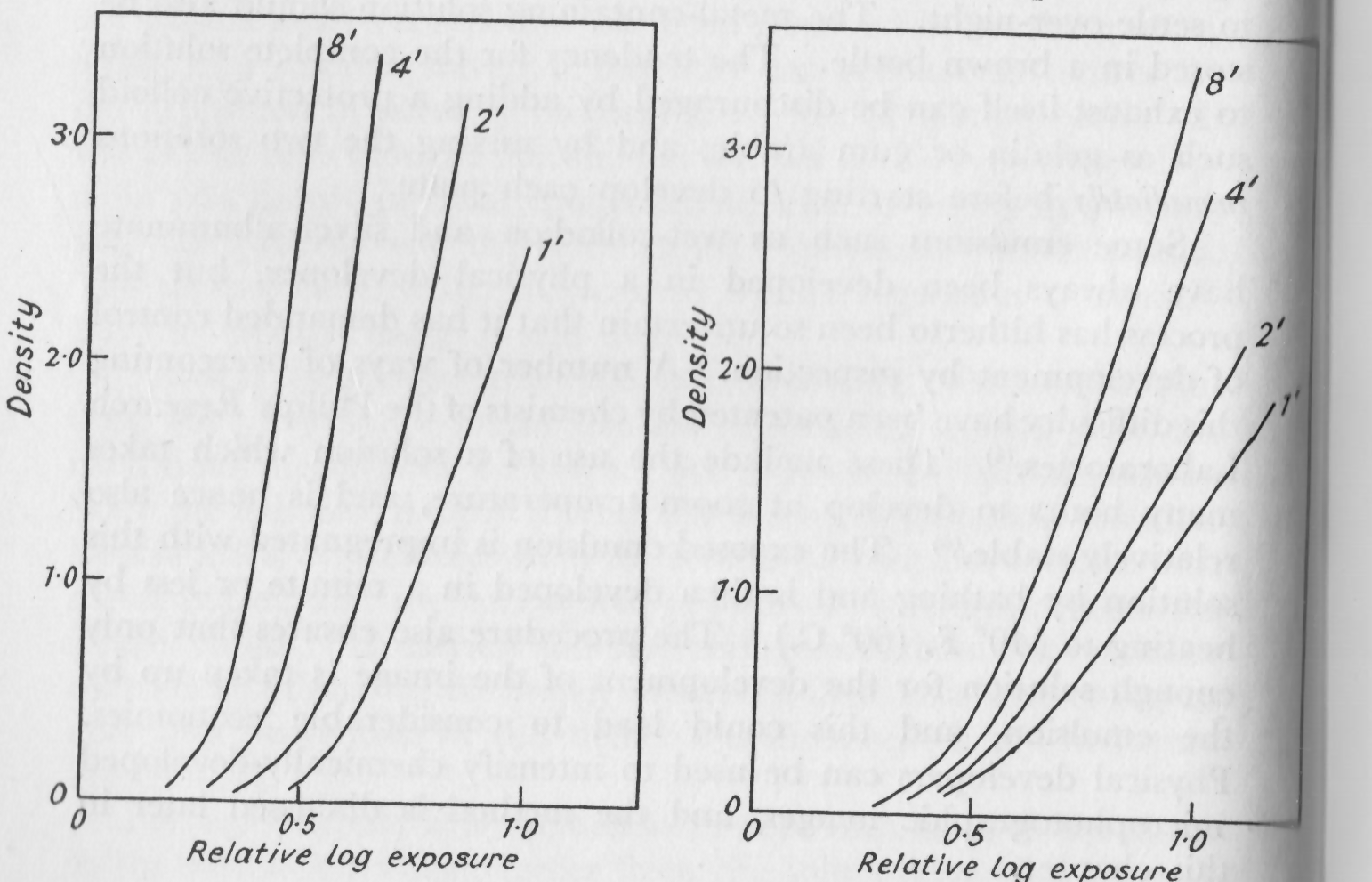
* Both these chemicals are *very corrosive*, and should be handled carefully.

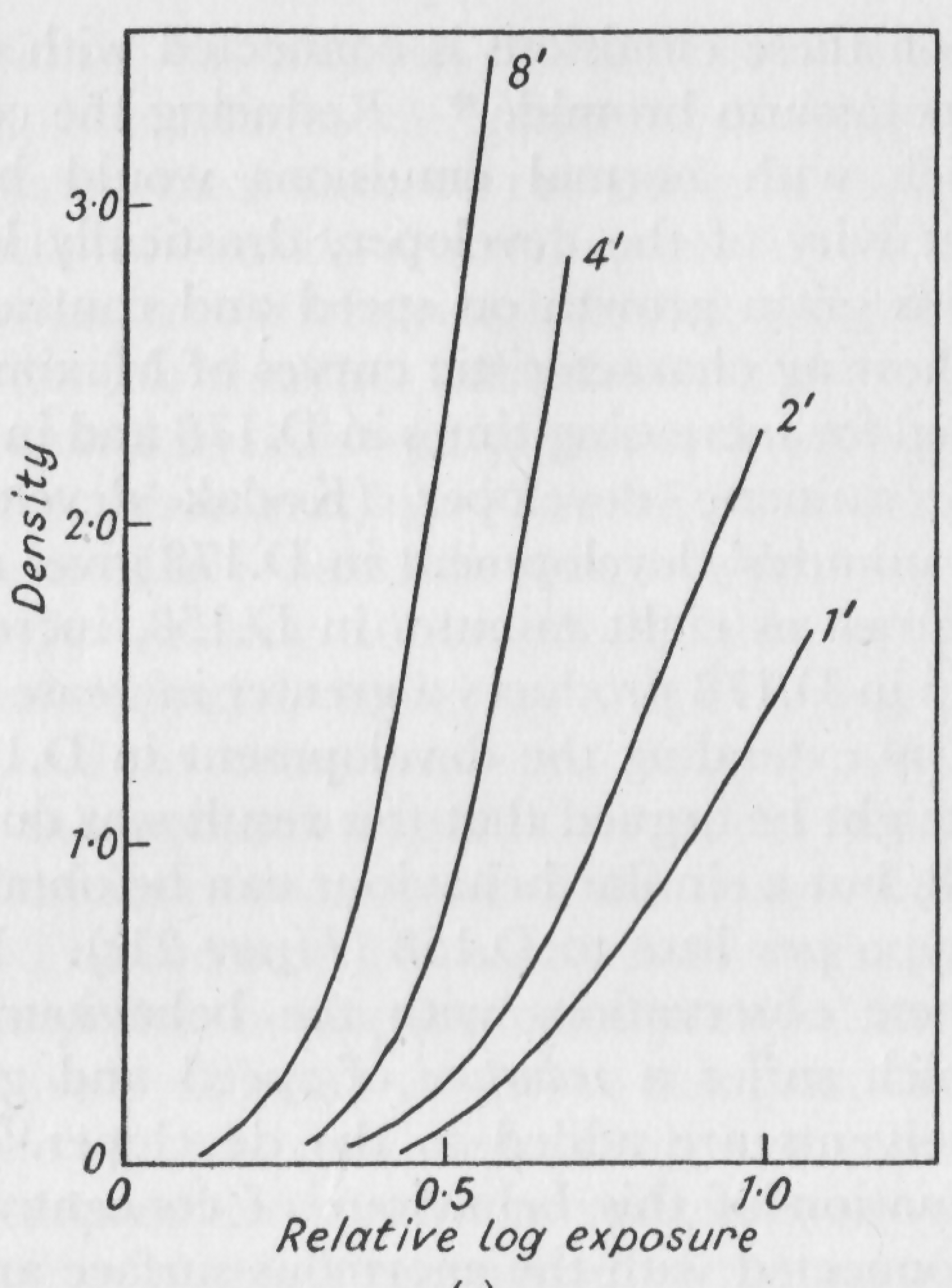
The effective emulsion speed given by chemical development depends primarily on the ability of the developer to distinguish between unexposed grains and those having received only a small exposure. The general experience is that the speed is mainly a characteristic of the emulsion, and is dependent to a relatively minor extent on the composition of the developer.⁽⁶⁾ With extreme-resolution emulsions, however, the simple picture given above is only a part of the story. One would, for instance, expect that the minute size and large specific surface of the grains in a concentrated-Lippmann emulsion should permit them to be reduced rapidly, so that development should be completed more rapidly than in coarser-grained emulsions. The reverse is in fact true. The density given by Maximum Resolution plates, for example, continues to grow with development time long after a " process " emulsion would have completed its development. The density increase on this type of emulsion in such cases is accompanied by an increase in the size of the silver particles until they are much larger than the grains of the unexposed emulsion. This effect is particularly marked at lower densities, and is accompanied by striking changes in the image colour. The increases in developed grain size and in density are influenced by silver-halide solvents such as hypo, or a high concentration of potassium bromide. Thus it can be shown that the special action of Kodak developers D.8 or D.178 in giving



(a) (b)

Fig. 21. *Growth of Density on Maximum Resolution Plate.*

(*a*) With development for series of times (figures denote minutes development at 70° F.) in Kodak D.178 (2 parts plus 1 part water).
(*b*) as (*a*), but with D.158 (1 part plus 1 part water).



(c)

Fig. 21. *Growth of Density on Maximum Resolution Plate.*

(*c*) as (*b*), but with 2·5 grams/litre sodium thiosulphate added to working solution.

high contrast on these emulsions is connected with their high concentration of potassium bromide.* Reducing the concentration of bromide, which with normal emulsions would be expected to increase the activity of the developer, drastically lowers it. The influence of this grain growth on speed and contrast is illustrated in *Figure* 21, showing characteristic curves of Maximum Resolution plates developed for increasing times in D.178 and in a conventional " Elon-" hydroquinone developer (Kodak developer D.158 *). Although two minutes' development in D.178 gives about the same speed and contrast as eight minutes in D.158, increasing the time to four minutes in D.178 produces a greater increase in density than was obtained by extending the development in D.158 from 4 to 8 minutes. It might be argued that this result was due to the caustic alkali in D.178, but a similar behaviour can be obtained by adding $2\frac{1}{2}$ grams of hypo per litre to D.158 (*Figure* 21*c*). It is interesting to contrast these observations with the behaviour of high-speed emulsions, which suffer a *reduction* of speed and graininess when silver-halide solvents are added to the developer.(7)

The explanation of this behaviour of concentrated-Lippmann emulsions is connected with the enormous surface area of the silver halide. One gram of silver halide in Maximum Resolution emulsion has a surface area of about 500 square feet (50 square metres), or about 200 times the superficial area of the plate on which it is coated. This allows the silver halide to dissolve rapidly in any solvent in the developer, which is thereby transformed into a physical developer as soon as it enters the emulsion. The small silver particles produced by chemical development of the exposed grains are effective nuclei for physical development, and the developed grains will thus tend to grow at the expense of the unexposed grains. The local drop in the silver-salt concentration, which follows deposition of silver on these nuclei, permits the dissolution of the adjacent unexposed grains to continue. As a result of this mechanism it is clear that the greatest increase of grain size will occur where the number of nuclei is small and the supply of silver halide from the unexposed grains is large ; namely, in the areas which have received the smallest exposures.

The effects of this complex chemical and physical development process are of importance for the processing technique of many fine-grain emulsions. In nuclear-particle emulsions (see Chapter 13), for instance, it results in the grains developing to a diameter substantially greater than that of the undeveloped grains. This enables the tracks of weakly-ionizing particles to be seen more easily, but can cause tracks of strongly-ionizing particles to become " clogged " so that less detailed information can be obtained from them. So long as it is not allowed to go too far, this grain growth is also useful in microphotography. The effective increase in emulsion speed is particularly valuable when concentrated-Lippmann plates are used for making intermediate negatives by direct reduction from an original drawing by reflected light (Chapter 8). Any gain in speed to counteract the long exposure required is valuable, while the resolution needed in an intermediate negative is not so great that some coarsening of the image structure is likely to be harmful. The increase of contrast derived from grain growth can be used to improve the apparent sharpness of line images, with which it is relatively difficult to detect the granular structure of the image (*Figure* 8*a*). It also seems likely that this sort of grain growth makes it possible to obtain sufficient density when the image is confined to a small proportion of the emulsion thickness by optical sectioning (Chapter 9). In this case the grains in the exposed layer of the emulsion can acquire silver obtained from the unexposed emulsion layers.

Care to avoid excessive grain growth is particularly necessary when making continuous-tone images, and when concentrated-Lippmann emulsions are used for microradiography (Chapter 13). Grain growth is also likely to be obtrusive when line images are made with an optical system which fails to produce a really sharp line. Unsharp lines always show a fringe with a very low density, and the greatest effect of grain growth will therefore be seen at the edge of the fringe. This results in a line having a central black core flanked with a ragged fringe of coarse grains. The physical development accompanying the use of a solvent developer may also permit some stain to form. This consists of exceedingly minute silver particles giving a yellow or orange colour, which has sometimes been mistaken for residues of the sensitizing dye. Stain can be prevented by not pushing the development too far, and techniques for removing it are described later in this chapter.

It is thus apparent that physical development in chemical developers may have both good and bad effects. The influence of physical development grows progressively with time, so that a brief development may give an image of fine structure and moderate contrast produced entirely by chemical development, and lengthening the time gives more and more grain growth. With moderate degrees of physical development the adverse effect of coarsening of image structure is often cancelled by improved contrast. Numerous resolution tests on Kodak Maximum Resolution plates have shown that 3–4 minutes' development at 68° F. (20° C.) in D.178 (two parts of developer to one part of water) gives optimum sharpness for line images. Although the developers D.178 and D.158 are recommended for these plates, there is little doubt that equivalent results could be obtained with other formulae. The fine grain and high resolution are primarily properties of the emulsion, and only grossly inappropriate treatment would be expected to spoil the results completely. The reader would, nevertheless, be well advised to use the recommended developers, since their suitability has been confirmed by tests extending over several years.

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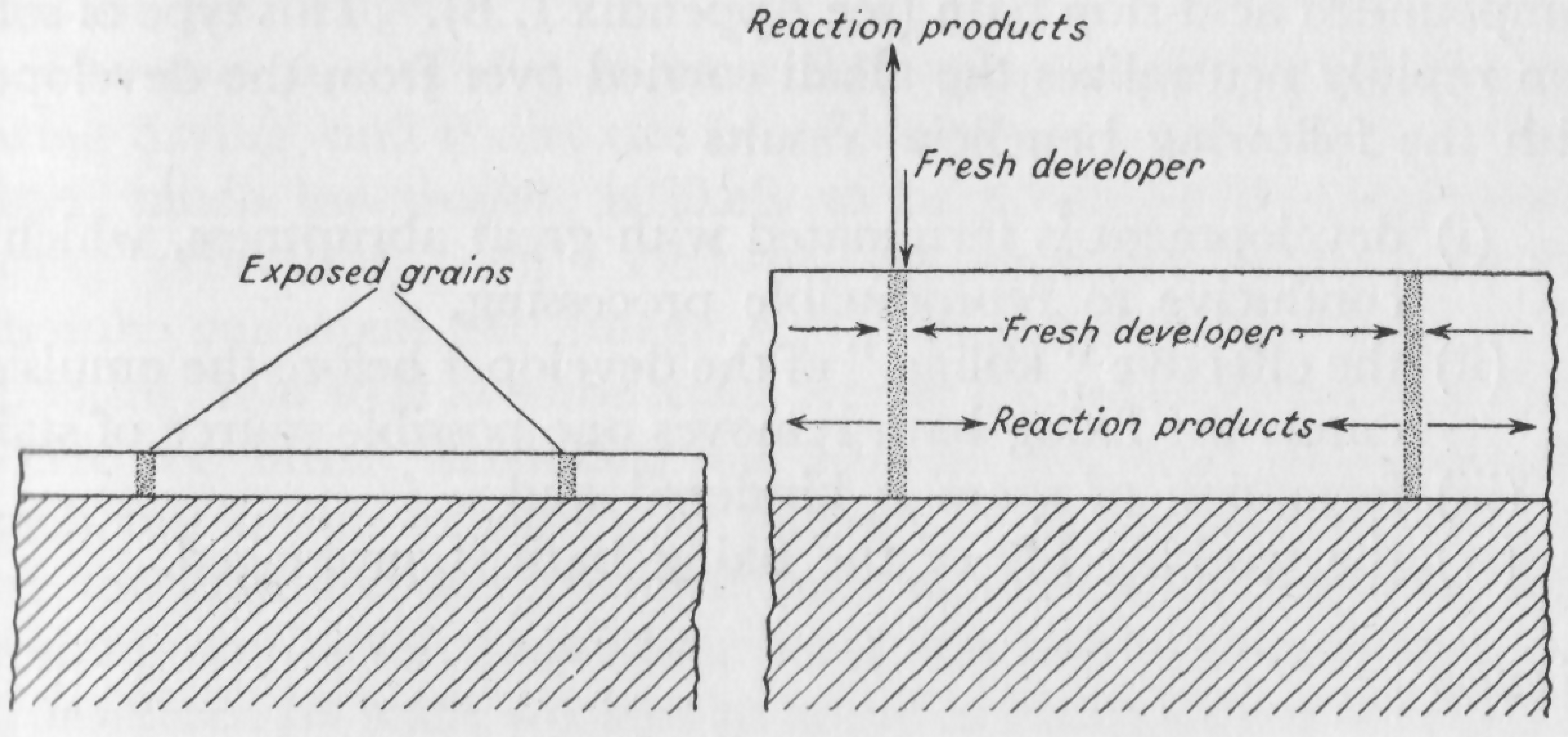
* See Appendix I, A for formulae.

Special Conditions in the Development of Microphotographs

Certain conditions not usually found in normal photography occur during the development of truly microscopic images. The images may, for instance, often occupy only a small proportion of the area of the plate, and may consist of lines narrower than the thickness of the dry emulsion layer. During processing the width of such lines will only be a small fraction of the thickness of the swollen emulsion, and sideways diffusion of development-reaction products out of, and fresh developer into, the image of the line will be more important than diffusion between the solution and the emulsion layer as a whole (*Figure* 22). Agitation of the solution, however, mainly influences diffusion between the solution and the emulsion, and can therefore be expected to have little effect on the development of such fine lines.

The small size of the exposed areas means that the passage of a number of plates through the developer will produce relatively little exhaustion of the solution. Under these conditions atmospheric oxidation may consume more developer than reduction of silver halide, and it should prove economical to develop in a deep vessel such as a beaker or a small accumulator jar. The reduction of the ratio of surface area to volume of the solution lessens the rate of atmospheric oxidation, and absence of agitation is unlikely to spoil the results.



(a) (b)

FIG. 22. *Diffusion in Development of Fine Lines.*

(*a*) Dry emulsion layer with exposed lines narrower than emulsion thickness.
(*b*) Diffusion processes during development of swollen emulsion layer.

Control of the development process plays an important part in microphotographic technique, since small differences in the exposure or in the effective emulsion speed given by development can produce a marked change in the quality of the image (see Chapter 9). The necessity for control is increased by the exceptional development characteristics of concentrated-Lippmann emulsions. Unlike most silver-halide-gelatin emulsions, which initially develop their density rapidly and thereafter show a much slower density increase, the density increase on concentrated-Lippmann emulsions shows no signs of ceasing within a convenient development time (*Figure* 21*a*). It is, therefore, not possible to obtain reproducible results by developing practically to completion, so that small changes in development time or temperature make little difference to the image. The small size of the images generally prevents convenient control of development by inspection, and control by the time and temperature should be used. Satisfactory reproducibility for most purposes should be obtained by maintaining the temperature within half a degree Fahrenheit (a quarter of a degree Centigrade) of the set value, and by timing development to within five seconds for a time of two minutes.

Acid-stop Treatment

The precision and cleanliness essential for the processing of microphotographs is assisted by the use of an inexpensive and easily compounded acid-stop bath (see Appendix I, B). This type of solution rapidly neutralizes the alkali carried over from the developer, with the following beneficial results :

(i) development is terminated with great abruptness, which is conducive to reproducible processing,
(ii) the effective " killing " of the developer before the emulsion enters the fixing bath removes one possible source of stain,
(iii) formation of scum is hindered and
(iv) the working life of the fixing bath is prolonged.

Fixation

Silver-salt emulsions are normally fixed in a solution of sodium thiosulphate, which readily dissolves any undeveloped silver salt, but only attacks the developed silver image extremely slowly. Fixing baths are usually acidified to counteract stain, and contain a gelatin hardener to inhibit excessive swelling of the emulsion during washing (see Appendix I, C). The fine grain of microphotographic emulsions permits any slight milkiness of the layer to clear very rapidly, but the time taken for the hardener to react with the gelatin is the same as for other emulsions. The full fixing time recommended for concentrated-Lippmann emulsions should therefore be given, but should not be greatly exceeded, because of the possibility of a gradual reduction of density.

Washing and Drying and Preservation of Cleanliness

Microphotographic images are easily spoiled by contamination of the emulsion surface during exposure or processing. The contamination may come from the atmosphere, or from any of the processing baths, or from the wash water. Washing and drying are particularly critical operations for preserving cleanliness, and the whole subject of cleanliness in handling is appropriately discussed in the present section.

The problem of obtaining clean microphotographic images can be attacked in two quite different ways. One theoretically effective method is to handle the emulsions in solutions and in an atmosphere free from all dirt particles with a length of more than a micron or so. The alternative, which we shall consider first, is to concentrate the precautions at the stages which are really critical for the cleanliness of the images.

The presence of dirt is most damaging during exposure and during drying, and if dirt can be effectively removed at both these stages, much less trouble is likely to be produced by its presence during processing itself. Dirt on the emulsion surface during exposure can spoil the image either by casting shadows, or by refracting light so that some areas receive too much light and others receive too little. Knocking the edge of the plate firmly on the bench just before exposure, or passing a powerful jet of clean air over the emulsion surface have been suggested for removing dirt. Brushing with a soft camel-hair brush has also been proposed, but is considered by some workers to apply as much dirt as it removes. The influence of transparent dirt can be partially counteracted by exposing the emulsion while its surface is immersed in a liquid of high refractive index in contact with a cover glass. The refractive index of the dirt particles is likely to be much closer to that of the liquid (xylene may be used) than to air, and the disturbance of the light at the emulsion surface will therefore be much less. This is undoubtedly a messy expedient, but there are circumstances in which it might seem worth while.

Finger-prints can result in local variations of density having a bad effect on microphotographic images. This damage is most likely to result from touching the dry emulsion surface with greasy or damp fingers, or fingers bearing traces of processing chemicals. Their incidence can be greatly reduced by reasonable care, and should be completely eliminated by wearing clean, dry, cotton gloves. Damage is much less likely to result from touching the emulsion once it has swollen in a processing bath, nor should contact with small insoluble dirt particles in itself be harmful during processing. Serious trouble is, however, caused by leaving dirt on the emulsion during drying : the dirt may then adhere so firmly that it cannot be removed without leaving a scar. The cure is, therefore, to remove dirt from the emulsion just before drying, but it is also prudent to prevent too much contamination of the emulsion during processing.

Access of dirt to the emulsion surface during processing can be reduced by preparing the developer so as to prevent formation of lime scum (see Appendix I, A), by filtering all solutions and the wash water and (perhaps most important of all) by holding the emulsion surface vertical or facing downwards throughout processing.(8) Most dirt reaches the emulsion surface by simple sedimentation, and an astonishing improvement can result from the last precaution.

At the end of washing, dirt on the emulsion surface is only loosely held, and can be removed by wiping gently. The problem is how to remove the dirt with the minimum risk of scratching the emulsion surface. Lime deposits from hard water can be removed by soaking the plates after washing in a 5 per cent. solution of acetic acid, but the remainder of the dirt has to be removed mechanically. The success of this final stage of processing is assisted by handling the emulsion during development so as to avoid excessive swelling. For this reason the temperature of all the processing solutions should be no higher than is necessary, the emulsion should be thoroughly hardened during fixation, and the washing should not be needlessly prolonged. Another useful precaution is to soak the emulsion for a few minutes in a mixture of three parts of " industrial " or " surgical " spirit to one part of water. This causes the emulsion to shrink and become mechanically tougher.

Some of the loose dirt can be removed from the emulsion surface by a powerful jet of water, but the most certain method is to wipe down with a chamois leather or a viscose sponge. The author has found the following method to be relatively safe. At the end of washing the plates are left in the alcohol solution for at least ten minutes—they can safely be left in this solution for hours. The wiping is then done in two stages. In the first stage the plates are held emulsion-side down in the alcohol solution, and the fully saturated wiping material is passed gently over the emulsion surface. This treatment should disperse most of the dirt into the bulk of the solution, or at least into the pockets of solution contained by the wiping material. The wiping material is then wrung out, and is held so that it makes contact with the top edge of the plate to be wiped and is held against the emulsion surface only by its own natural springiness. It is then pulled smoothly down over the emulsion surface ; when necessary using a number of overlapping strokes until the whole area is covered. The aim of the second stage of wiping should be to remove as much as possible of the surface liquid, and with it the last traces of dirt. The removal of the liquid during wiping should be watched by holding the plate at such an angle that the eye sees an image of the room light reflected at the emulsion surface. The same method of inspection should be used to examine the surface when the small residual beads of liquid have evaporated, about five minutes after wiping. The surface should then appear smooth, with very few bumps. If it is obviously still dirty, the plate may be returned to the alcohol solution, and the wiping repeated.

The success of this wiping procedure depends on cleanliness and skill. After each use the wiping material should be squeezed out in several changes of clean water, and then left in a dust-free cupboard to dry. The necessary skill can only be obtained by practice, but it is not necessary to use exposed and developed plates for this purpose. Excellent experience can be obtained by wiping unexposed plates which have been fixed and washed.

Dirt reaching the surface of a gelatin emulsion during drying is likely to be trapped by the " tacky " surface, and may then stick almost as firmly as dirt left on the emulsion at the end of the washing. It is important to remember, however, that the only particles to be trapped in this way are those which actually touch the emulsion surface, and the number of these can be greatly reduced by drying the plates emulsion-side downwards. Dirt which falls on the back of the plates is harmless, as it can all be polished off when the plates are dry. When the plates are dried in this position dirt can only reach the emulsion as a result of air currents. It is therefore advantageous for the work-room to be free from draughts, and a high level of cleanliness must also lessen the risk of dirt reaching the emulsion. Another good method for obtaining fairly rapid drying combined with freedom from dirt is to support the plates face downwards over a dish containing a desiccant such as silica gel or anhydrous calcium chloride. For rapid drying the emulsion surface should be no more than two-fifths of an inch (1 cm.) from the surface of the desiccant, and the dish should be covered so that the air-space between the emulsion and the desiccant is shut off from the outside atmosphere. Whatever method of drying is used, the hazards of this stage are terminated as soon as the emulsion has passed beyond the " tacky " condition. Dry dirt reaching it after this can be safely removed by wiping gently with a " Selvyt " cloth.

The methods described above are analogous to antisepsis, in that they are devised to control the harmful effects of dirt rather than to eliminate dirt completely. The rigour with which these precautions should be applied depends on the circumstances in which the work is undertaken. The amateur making relatively few images for his own satisfaction can either adopt most of the suggested precautions, or can make more images but with less care, and then select the cleanest when the work is completed. The choice for commercial operators will be determined by the combination of precautions giving the lowest cost per satisfactory image. When a very high standard is required, as in the case of scales to be viewed in the focal plane of an optical instrument (Chapter 11, page 205), " antisepsis " alone may prove insufficient : precautions analogous to asepsis may be needed.* It may be necessary to construct tiled darkrooms which can be regularly hosed down, and are supplied with specially filtered air. The operators may have to wear dust-proof clothing of the type used in certain sections of the photographic or pharmaceutical industries. These expensive precautions are likely to prove most successful when combined with the commonsense (" antiseptic ") precautions described above. Moreover, the best results are only likely to be obtained by operators who have gradually worked up their technique by progressive improvements over a period of many weeks or even months.

Prevention of Emulsion Distortion

Although silver-halide-gelatin emulsions coated on glass normally reproduce the dimensions of the image printed on them with commendable faithfulness, there is some tendency for small distortions to occur, particularly when the plates are not processed correctly. Methods already suggested for preventing excessive swelling should, for most purposes, suffice to eliminate a harmful degree of distortion, but extra precautions can be taken when the dimensional stability of the image is particularly important. Distortion may occur in the rinse bath between development and fixation, as a

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* A valuable summary of information on this subject has been given by D. E. P. Jenkins. "Clean Rooms for Special Valve Assembly", *Instrument Practice*, 8, 1085, 1954.

result of the rapid rate at which the emulsion swells in this stage. This danger can be avoided by using a non-swelling stop-bath such as Kodak formula SB.4 (Appendix I, B). Another precaution, recommended by Cooksey and Cooksey for astronomical or spectroscopic photography, is to anneal the emulsion layer before exposure.(9) They considered that the emulsion on factory-dried plates is in a state of strain, which can cause distortion when the emulsion is swollen. They released the strain by swelling the emulsion slightly in an aqueous-alcohol solution, and dried slowly before exposure. This treatment was reported to lessen distortions substantially, but the risk of contaminating the emulsion surface makes such bathing treatments inadvisable for microphotography. Essentially the same result should be obtained without this risk by supporting the unexposed plates (emulsion-side down) over a dish of water for an hour or two. This permits the emulsion to swell enough to become quite plastic, without any liquid actually touching the emulsion surface.

After-treatment of Developed Images

In many branches of photography developed silver images are submitted to various chemical after-treatments. The density and contrast of the image can be decreased by *reduction* or increased by *intensification.* These processes are used to compensate for errors in exposure, or to give a contrast or line sharpness unobtainable by simple development. The image can also be converted to some other form in order to modify its colour or permanence, or to give it other desired properties, without substantially altering the density. Special care is needed in the application of these techniques to microphotographs, since the images can so easily be spoiled by coarsening of the grain structure, or by dispersing the material of the image or by attacking images of lines of different widths at relatively different rates. Because of these pitfalls the reader is advised to apply these methods only when they are essential for obtaining a desired result. Errors in exposure should preferably be corrected by making fresh images, rather than by reduction and intensification which are quite likely to give inferior results and waste time. The following two sections, therefore, are only intended for guidance in the small proportion of cases in which a modified exposure or development cannot give the desired result.

Reduction

Reduction can be used to remove silver stain, or to clean the edges of ragged lines, or to prepare images for subsequent intensification.

Silver stain consists of very minute particles of silver, and Henn, Crabtree and Russell have shown that slow-acting reducing solutions, such as an acidified ammonium-thiosulphate solution, can attack the stain image substantially more rapidly than an ordinary developed image (Appendix I, D). This method should be useful when development has been forced to increase emulsion speed with a resultant formation of stain, or when stain is seen on a valuable image (or batch of images) after the work is almost complete.

The ammonium-thiosulphate reducer contains a high concentration of a feebly acting bleaching agent, but it is often also useful to employ a low concentration of an active agent. Such solutions can be compounded by adding 0·2 per cent. (or less) of potassium ferricyanide to 1 per cent. potassium bromide or 10 per cent. sodium-thiosulphate solution. The solution tends to become locally exhausted as soon as it reaches an area with a high silver content, but will tend to continue acting in low-density areas where the rate of consumption of ferricyanide is not much greater than the rate of replacement by diffusion from the bulk of the solution. The proportion of the silver removed from a low density may, therefore, be much higher than that removed from a high density, and the edge of a blackened area may be attacked more rapidly than the centre. This is the mode of operation of the " cutting " reducers which are used to sharpen the dots in half-tone photomechanical negatives. They can be used in the same way to sharpen the lines in microphotographs, but there is a danger that they may spoil the images by rounding off corners, by attacking the ends of lines preferentially and by producing proportionally greater reductions in the widths of fine lines. Whenever possible, reduction should therefore first be tried on a waste image ; it is also advisable to interrupt the process at frequent intervals so that the influence on line quality can be assessed by examination at a suitably high magnification. Another precaution is to effect the reduction in two stages, by treating first in a ferricyanide-bromide solution. This does not immediately remove the image from the layer in the way that hypo-ferricyanide solutions do, but merely bleaches it to lightly coloured silver bromide. The extent of the bleaching can be followed with the microscope, and when the desired action is achieved the silver bromide is simply removed by re-fixing the plate. If the bleaching is accidentally carried too far, however, the original image can be restored by treating in a developer in the light until all the silver bromide is reduced back to silver. A tentative procedure of this type has much to recommend it when dealing with these delicate and chemically-fragile images.

For reasons which are explained in the next section, cutting reducers are useful for ensuring complete absence of nuclei between the lines when the images are to be subsequently intensified.

Intensification

Developed silver images can readily be intensified by bleaching them to an insoluble silver salt, using a solution which also causes the simultaneous precipitation of the reduced bleaching agent (formed by reaction with the silver) as a by-product. Such processes involve the risk that the reduced bleaching agent may diffuse sideways in the gelatin before precipitation, and hence spoil the sharpness of the images. This difficulty is avoided by choosing processes giving very insoluble by-products, and by balancing the solution so that the rate of precipitation of the by-product is at least as rapid as the bleaching of silver which causes its formation. Of the many intensification processes known, the mercury intensifier (Appendix I, D) seems particularly suitable for treating microphotographs. The silver image is first bleached in a solution of mercuric bromide :

$$Ag + HgBr_2 \rightarrow (AgBr)\ (HgBr)$$

giving a white deposit of the mixed mercurous-silver bromide. After thorough washing this is blackened in a non-staining developer, forming a mixture of metallic silver and mercury. Further intensification can be obtained by repeating the whole process.

A basically superior method for intensifying microphotographs is provided by physical development, in which the extra material added to the image is selectively deposited on the centres produced by the preliminary development. This process avoids any risk of sideways spreading of the image as a result of diffusion of reaction products. Now Arens (10) has shown that the density obtained on physical development is determined mainly by the number of nuclei present, and not on their original size. The highly-dispersed silver image formed by chemical development of Lippmann emulsions is thus in a more favourable condition for physical intensification than the coarser deposit formed by faster emulsions. Extraordinary increases of density can, in fact, be obtained by physical intensification of these emulsions (*Figure* 20).

The very potency of this method means that it should be handled with care and discretion. The standard of cleanliness required is the same as for the physical development of latent images (see page 57). If carried to completion physical intensification can give very coarse grain (*Figure* 23), and sufficient intensification of microphotographic images is usually obtained when the process is stopped at an early stage. The density obtained will then depend on the rate of supply of metal from the solution, as well as on the number of nuclei present. In these circumstances, the number of nuclei present in an original image of quite low density may result in a high density after intensification, and the proportional rate of increase of density is likely to be greatest for the lowest densities of the original image. It is therefore important that the images to be intensified should have absolutely no fog grains or stain in the background, as the background density may otherwise build up from a previously imperceptible deposit. Plates to be physically intensified should therefore, when possible, be processed with special care. Only a brief development (1 to 2 minutes in D.158) is needed, and this should be followed by an acid-stop bath. Application of a " cutting " reducer, such as the ferricyanide-bromide or ferricyanide-hypo solutions described above, can be used to remove stain or background grains resulting from light scatter or development fog. As the increases of density obtainable are so great, an image of satisfactory density can be obtained even after the chemically-developed image has been reduced until the lines are quite faint. The more drastic the reduction the less likely are nuclei to be left in the background, but the reduction should be carefully controlled to prevent excessive rounding of the corners of the image.

Since physical intensification consists in the continued growth of the silver particle from each exposed grain, until sufficient density is obtained, the structure of the image is inevitably coarsened. The final result will, nevertheless, be much sharper than an image of the

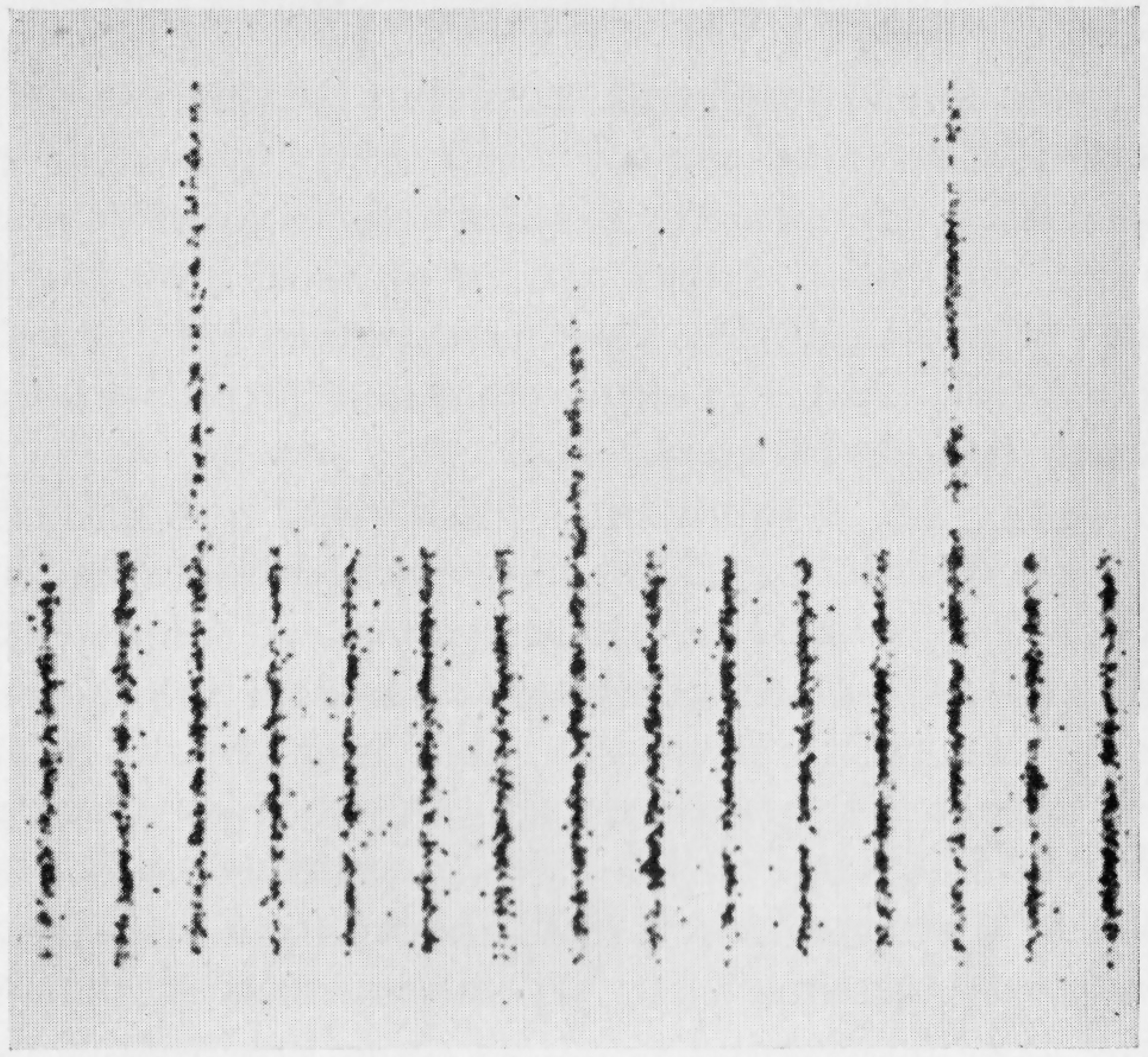

FIG. 23. *Result of Excessive Physical Intensification.*

The grains of this image on Maximum Resolution emulsion (×540) have been enlarged by intensification to the grain size of a document-copying emulsion, but the improvement of resolution due to low turbidity at the instant of exposure is not all lost (compare *Figure* 8).

same grain size produced by chemical development of a coarser-grained emulsion (*Figure* 23). The spatial relationships of the grains to each other still depend on the optical properties of the emulsion at the instant of exposure, and the greater light scatter of the coarser-grain emulsion will cause the edges of the lines to be more ragged, even though the image is built up from developed grains equal in size to those of the intensified Lippmann emulsion (*Figure* 8*b*).

Intensification by physical development is particularly useful when exceptionally difficult images have to be made, such as those in which fine clear lines are required in the middle of a large dark background. With images of this type, the minimum exposure giving adequate density by direct development is often sufficient to cause lens flare or light scatter in the emulsion to veil over the lines. This can be avoided by using a lesser exposure, which reduces the intensity of the flare and scattered light below the threshold at which the grains show any latent image. The resultant " ghost " image shows less image spread, and can be brought up to a useful density by physical intensification. A further feature of physical intensification is that it enables the image to be directly strengthened by metals other than silver. Thus physical intensification in a mercury physical developer gave an image with a higher opacity to X-rays than could be obtained from a silver image (Chapter 13).

Toning

Various processes can be used to modify such properties as the colour and durability of microphotographic images, but as with intensification, these must be selected to give the minimum sideways diffusion of the image. The following uses have been found for toning processes in microphotography. Goldberg (11) treated the images produced in his print-out emulsion with a gold toner of the type which used to be employed with printing-out (daylight) papers. This method gives a pleasing cold-blue tone, and the image is very permanent. The same process might be used with other emulsions with which plain development gives an unpleasant image colour. There are many other ways of modifying the colour of silver images, of which bleaching and re-development in a dye-coupling developer is potentially the most interesting. A process for making coloured microphotographs might be based on this principle, but the couplers should be selected to deposit the dye very close to the developed silver particles.

In their graticule factory the firm of Möller preserved valuable master negatives by bleaching the silver image to silver iodide (Chapter 11, page 213), and it was found that the images were still in perfect condition after storing for many decades.(12) The same firm also converted graticule images from silver to platinum, so that they could be burned into the surface of the glass on heating nearly to the softening point of the glass. Conversion of microphotographic images to silver iodide has also been carried out in the presence of radioactive iodide ions, to give radioactive images suitable for testing the resolution of autoradiographic emulsions (Chapter 13).

Miscellaneous Processes

Production of Stencil Images

As an alternative to the use of bichromated colloids, stencil images can be made from silver-halide-gelatin emulsions. One method is to use an emulsion which has not been hardened in manufacture, and then harden the emulsion layer image-wise in one of two ways. If sufficiently-alkaline developers containing catechol (pyro-catechin) or pyrogallol or hydroquinone are compounded with a low concentration of sulphite, the oxidized developing agents produced by the reduction of the exposed grains react with the gelatin and harden it in the immediate vicinity of the developed silver.(13) After development in such " tanning " developers, the stencil is formed by washing away the unhardened unblackened areas in hot water. Image-wise hardening for this type of procedure can also be obtained after developing in a normal non-hardening developer, by bleaching the developed silver with an oxidizing agent whose reduced form hardens gelatin.(14) Stencil images can also be made from developed images in hardened emulsion layers by using " etch-bleach " solutions containing cupric salts and hydrogen peroxide (see Appendix I, D). The products formed when the cupric salt oxidizes the silver image are thought to catalyse destruction of the gelatin by peroxide. The developed areas are thus washed away, and the tone values of the image are reversed when the remaining emulsion is developed.

The usefulness of these stencil processes for microphotography is rather problematical. They possess the advantage of enabling stencil images to be made with an exposure many hundreds of times less than that needed for bichromated colloids, but the physical behaviour of the washed-out stencil causes only indifferent resolution to be obtainable from layers with the thickness of factory-coated gelatin emulsions (Chapter 3). There is, however, no obvious reason why this type of procedure should not be operated with much thinner coatings of a Lippmann emulsion made by " whirling ". This possibility of combining the advantages of stencil images with the speed of the Lippmann emulsions remains to be explored.

Development for Reduced Contrast on Concentrated-Lippmann Emulsions

The methods used to ensure the very fine grain of commercial concentrated-Lippmann emulsions result in photographic images with a high intrinsic contrast and small latitude. The high contrast is normally an advantage, since much extreme-resolution photography involves the making of " line " images, and high contrast assists in the making of sharp lines. Lower contrast can certainly be obtained on these emulsions by using a " soft-gradation " developer, or by developing in very dilute solutions, but these methods cannot increase the latitude of the emulsion and therefore give an image of poor maximum density (curve *B*, *Figure* 24).

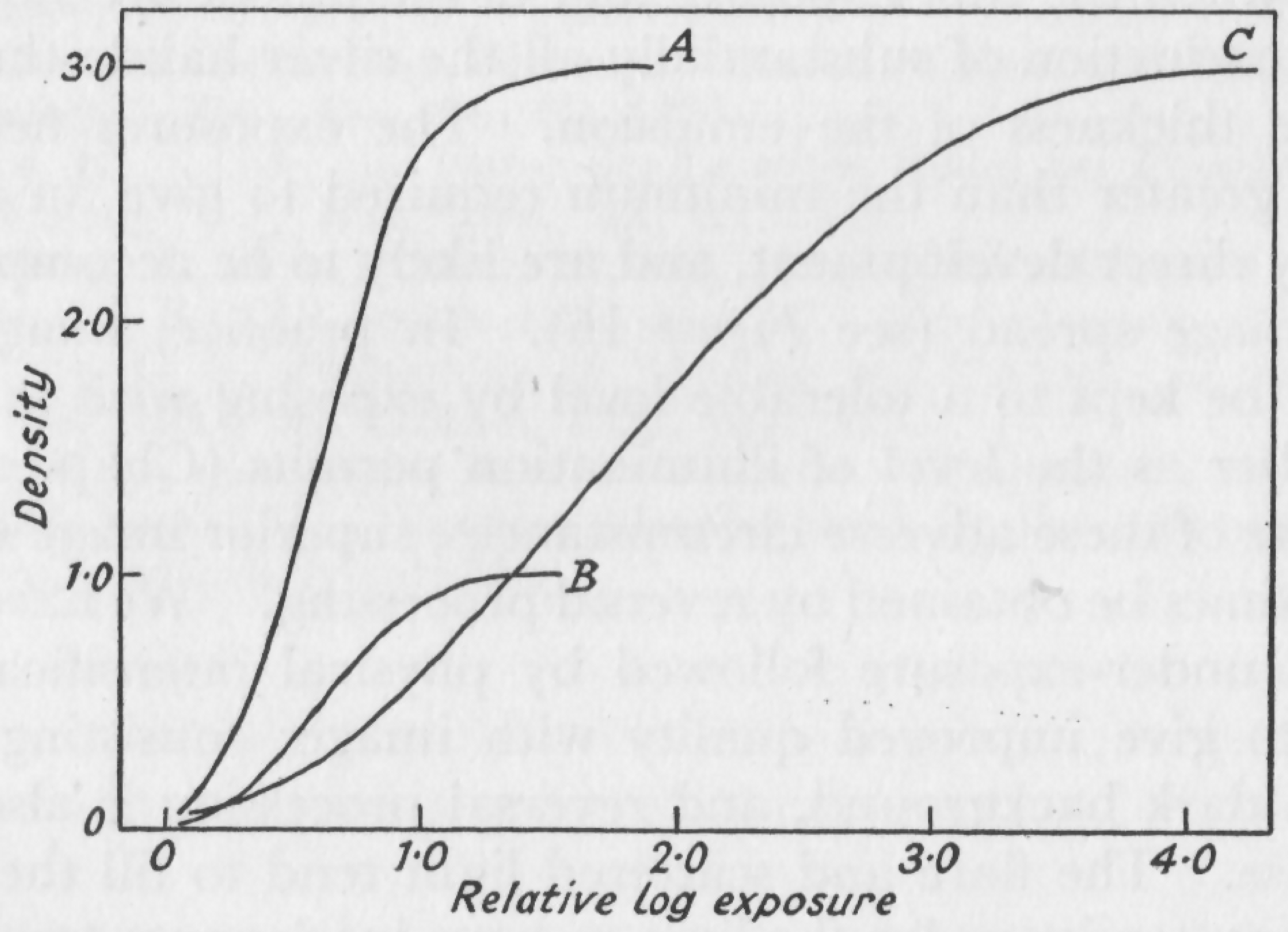

FIG. 24. *Tone Reproduction by Concentrated-Lippmann Emulsion.*

(*A*) Curve produced by moderate-contrast developer.
(*B*) Reduced contrast and maximum density produced by dilute developer.
(*C*) Result required for continuous-tone work.

Continuous-tone images can be made more satisfactorily by using emulsions of lower intrinsic contrast, such as wet-collodion or collodion print-out, or by using a concentrated-Lippmann emulsion with a low-contrast intermediate negative. On the other hand, a soft-gradation developer (Appendix I, A) is definitely useful for producing low-contrast images on " negative " emulsions having moderate or high latitude.

Reversal Processing

Concentrated-Lippmann emulsions, like other silver-halide-gelatin materials, can be processed to give a direct-positive image by the operations of developing, bleaching out the developed silver, fogging and re-developing (Appendix I, A). The reversed image is formed from the silver halide which is not blackened by the first development, and the resolution obtainable is consequently impaired in two ways. In the first place the reversed image is necessarily formed throughout the whole emulsion thickness, so that the advantage derived from focusing high-aperture objectives right in the surface of the emulsion can no longer be obtained (see Chapter 9). Reversed images are, moreover, only considered satisfactory when the transparent parts are completely clear. This is only achieved when the first exposure and development are sufficient to cause the reduction of substantially all the silver halide throughout the entire thickness of the emulsion. The exposures needed are therefore greater than the minimum required to give an adequate density by direct development, and are likely to be accompanied by greater image spread (see *Figure* 15). In practice, image spread can often be kept to a tolerable level by exposing with as deep an orange filter as the level of illumination permits (Chapter 3).

In spite of these adverse circumstances, superior image sharpness can sometimes be obtained by reversal processing. We have already seen that under-exposure followed by physical intensification can be used to give improved quality with images consisting of clear lines in a dark background, and reversal processing is also helpful in this case. The flare and scattered light tend to fill the lines in, whereas any tendency for the lines to have inadequate transparency is simply cured by increasing the exposure if a " negative " transparency is copied with reversal processing. When used with commercially-coated Lippmann emulsion, reversal processing has been found to give satisfactory line quality down to a line width of five microns.

Reversal processing also provides a simple method for obtaining a negative consisting of one or a series of small negatives on a plate whose whole emulsion area is otherwise blackened. This method is particularly suitable for making negatives of large graticule images by projecting successive elements of the image one after the other on a large plate.

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CHAPTER 5

The Objective

Objectives for Document Microphotography

IN CHAPTER THREE microphotography was shown to comprise the production of three types of image, namely, minute (or microscopic) images, instrument scales, and commercial document copies. The last type is distinguished from the others by the different criteria which are used in selecting the objective. Commercial document-copying processes are commonly operated at reduction ratios of 15 to 35 diameters, and the lens-to-copyboard distance may hence need to be as large as thirty-six times the focal length of the objective used. To make the equipment sufficiently small for easy transportation and installation in practically any office, it is the practice to use objectives of short focal length—usually no greater than an inch or two. The diagonals of the negatives made by commercial document-copying apparatus are normally at least equal to half the focal length of the objective, which means that the angular field of view is not much less than that of " pictorial " cameras. In document copying, moreover, the legibility of the characters in the extreme corners of the field is just as important as on the axis, whereas the conventional concentration of interest of pictorial photographs well away from the corners means that reduced sharpness in the corners can often pass unnoticed. For this reason manufacturers of document-copying equipment have given special attention to the provision of objectives giving exceptionally high sharpness right up to the corners of the negative. Lenses designed for pictorial photography often prove less satisfactory in this respect.

Since the essential quality of objectives for document microphotography is *uniformity* of sharpness over the field, there is little point in demanding exceptionally high resolution on the axis. The usefulness of high axial resolution is also restricted by the fact that

the emulsions used must have a minimum level of speed, which in practice sets an upper limit to the resolution obtainable (see Chapter 3). These emulsions are, in fact, unlikely to be capable of detecting small residual aberrations which might be intolerable for extreme-resolution photography.

Because of the economic importance of document microphotography, the problem of providing suitable objectives and the techniques for using them to the best advantage have already been worked out. A reader proposing to carry out this work is thus likely to obtain satisfactory results with the minimum of effort by obtaining good equipment and following the manufacturer's instructions. He may, therefore, find that the remainder of this chapter does not directly concern him, since it deals with objectives for making the other types of microphotographic image, for which the choice of objective is much less " cut and dried ".

Objectives for Extreme Resolution

While lens designers are only too well aware of the shortcomings of photographic objectives, the performance obtained is commonly adequate for most photographic tasks. In practice, the limitations imposed by the objective often prove unimportant compared with the effects of graininess and light scatter in fast negative emulsions, even if unaccompanied by camera-shake or incorrect focus. It is probably true to say that the resolution given by high-quality photographic objectives is, for many purposes, sufficient to provide a reasonable margin for safety. Quite acceptable results can, therefore, be obtained even by an operator with but a rudimentary knowledge of their properties. In extreme-resolution microphotography, however, one is forced to work much closer to the limit of performance of the objective ; and it is therefore advisable to consider the objective as a working tool with its own qualities and limitations, rather than as a piece of equipment whose properties can be taken for granted.

The remainder of this chapter therefore deals with those properties of importance for this work, with the types of objective which may be used, with means for testing and selecting an individual objective and with the practical precautions needed to secure extreme resolution. While reading these sections, the reader should remember that the standard of sharpness demanded by extreme-resolution microphotography is completely beyond ordinary photographic requirements. He should, therefore, not be unduly disturbed if some of the tests cause him to detect deficiencies in the lens of his own camera. Defects which are serious for microphotography are often not detectable in ordinary use.

The Properties of Objectives

Focal Length

When an objective is focused on an object at a distance u, a real image is formed at a distance v from the objective. The object and image are then said to be at *conjugate foci*, and the distances u and v are related to each other by the equation :

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$

where f is the *focal length* of the objective.*

The focal length is an important quantity characterizing each individual objective, and is equal to the effective distance at which an image is formed when the object is at infinity. In conjunction with variations of the above formula, it allows many useful quantities to be calculated.$^{(1)}$ The degree of reduction, for instance, is equal to the object distance divided by the image distance, and this quantity can be evaluated by the formula :

$$\text{Degree of reduction } (R) = \frac{u}{v} = \frac{u - f}{f}$$

This shows how the degree of reduction is increased by increasing the object distance, or by using an objective of shorter focal length.

The practical applications of the simple lens formula are complicated by the fact that multi-component lenses are so thick that it is difficult to measure the *effective* object-to-lens distances with the accuracy needed for microphotography. The total object-to-image distance (i.e. $u + v$), however, is a quantity which can be measured readily,* and the degree of reduction can be calculated from an alternative approximate formula :

$$\text{Degree of reduction} = \frac{D - 2f}{f}$$

where D is the object-to-image distance.

With degrees of reduction of twenty or more, this formula gives results sufficiently accurate for many purposes, and the proportional error becomes still smaller at greater degrees of reduction.

Although it is difficult to measure the effective values of u and v directly, it is fairly simple to measure *changes* in these distances with reasonable precision. The lens formula is, therefore, useful for computing the changes in image distance resulting from a given change in object distance. This information is useful when focusing a distance piece, or when focusing an objective by altering the distance of the object plane (Chapter 6). Values calculated for a series of nominal focal lengths are tabulated in Appendix II, A.

More precise figures can be obtained by substituting the object distance (u) and the exact focal length (f) in the formula :

$$\text{Image distance } (v) = \frac{fu}{u - f}$$

The calculations can be simplified by computing the figures for a focal length of unity, when this takes the form :

$$v = \frac{u}{u - 1}$$

The values for an objective of any focal length are simply obtained by multiplying the results by the focal length of the objective. Values of the ratio $\frac{u}{u - 1}$ for a range of degrees of reduction are tabulated in Appendix II, B.

Consideration of the focal length provides a useful preliminary guide to the selection of an objective for any particular job. Microscope objectives of the same focal length made by different manufacturers frequently have much the same aperture, and are likely

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* In this version of the formula, the distances are measured from the objective. In formal optics it is more usual to relate the distances to the direction of the incident light, so that u becomes negative and the formula then becomes :

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

* With thick lenses u and v should, strictly speaking, be measured from *nodal points* which are separated by a finite distance. Thus the *effective* object-to-image distance is slightly different from the measured distance, but the error due to using the latter figure is small when high degrees of reduction are used.

to cover about the same useful field and give approximately the same resolving power. With decreasing focal length, the degree of reduction obtained at any particular distance, the angular aperture and the resolving power are all increased, but the useful field is decreased.

The Aperture

The aperture, or the relationship between the focal length and the effective opening of an objective, is another quantity of great importance. In the case of a single thin lens an approximate value for this ratio can be found by focusing the objective on an object at infinity, and then dividing the image-to-lens distance by the diameter of the lens (*Figure* 25*a*). With thick, complex lenses, however, the aperture has to be described with regard to the physics of image formation.⁽²⁾ When a lens is corrected for coma and spherical aberration (see below), as all satisfactory photographic objectives must be, all rays entering the lens parallel to the axis converge to a focal point on the axis. It can be shown that the

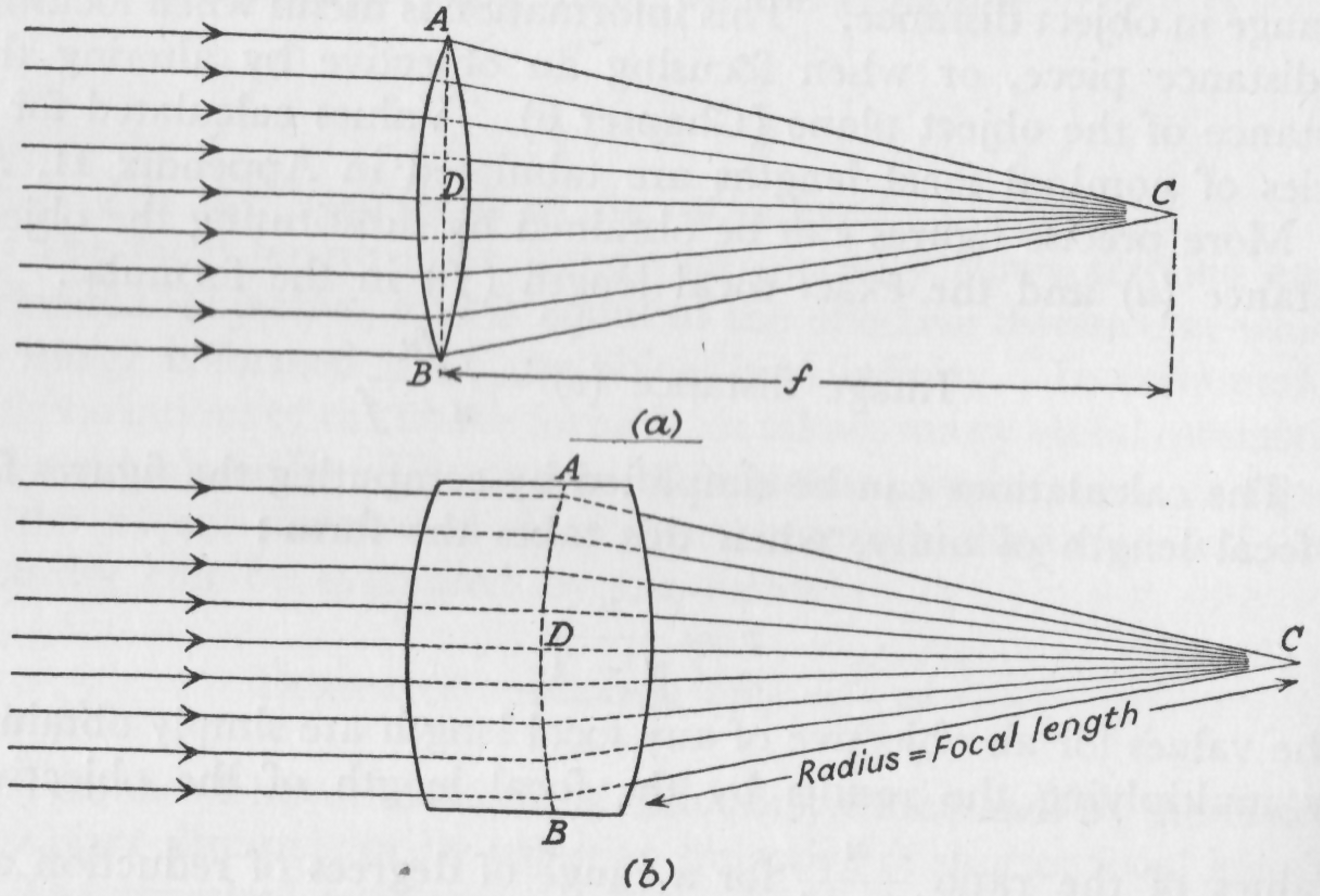


FIG. 25. *Apertures of Thin and Thick Lenses.*

(*a*) For thin lens, F-number $= \dfrac{CD}{AB}$

(*b*) For thick lens, F-number $= \dfrac{CD}{AB} = \dfrac{CA}{AB}$, since $CD = CA =$ focal length.

points at which they appear to change direction, if the rays entering and leaving the objective are projected forward and backward respectively, lie on a sphere with its centre at the focal point, and of radius equal to the focal length (*Figure* 25*b*). Now photographic objectives are described by their " F-number " or the ratio of the focal length to the effective diameter of the aperture. If θ is half the angle which this diameter subtends an image on the axis, it follows that:

$$\text{F-number} = \frac{f}{AB} = \frac{f}{2AD}$$

but

$$\frac{AD}{f} = \sin\theta,$$

hence

$$\text{F-number} = \frac{1}{2\sin\theta}$$

The angular aperture of an objective is, in fact, inversely proportional to its F-number.

The aperture of microscope objectives is usually defined by the *numerical aperture*:

$$\text{Numerical aperture (N.A.)} = n\sin\theta,$$

where n is the refractive index of the medium in which the objective is used.

In the case of " dry " objectives working in air, n is unity, the N.A. therefore equals $\sin\theta$, and from the formula for the F-number it follows that:

$$\text{Numerical aperture} = \frac{1}{2 \times \text{F-number}}$$

Since both the numerical aperture and the F-number are simple functions of the angle θ, equivalent values can be readily calculated. Table II shows that a low-power microscope objective with a moderate N.A. of 0·2 has the same aperture as a " fast " camera lens with an F-number of 2·5.

When diffuse illumination is used (Chapter 8), the brightness of the image is proportional to the square of the N.A. of the objective used, or inversely proportional to the square of the F-number. The aperture of a lens in addition influences the depth of focus and the useful flat field, and not infrequently also the aberrations

TABLE II

Connection between Numerical Aperture and F-number

Numerical aperture	*Equivalent F-number*
0·15	3·3
0·20	2·5
0·25	2·0
0·30	1·7
0·40	1·25
0·50	1·0
0·60	0·83
0·70	0·71
0·80	0·63
0·90	0·56

shown. As will be shown later, the resolving power of microscope objectives increases with N.A., but the depth of focus and useful flat field are decreased by increasing the aperture. Martin and Johnson (3) give the following table for the depth of focus of microscope objectives of different aperture :

TABLE III

Dependence of Depth of Focus on Aperture

Numerical aperture	*Depth of focus*
0·25	7·9 microns
0·50	1·9 ,,
0·75	0·8 ,,
1·25 (oil immersion)	0·4 ,, (in medium with $n = 1{\cdot}5$)

Colour Correction

The refractive index of glass decreases with increasing wavelength, so that a simple positive lens will have a longer focal length for red light than for blue (*Figure 26a*). The rate of change of refractive index with wavelength (dispersion) is an important property of glasses, and generally increases with increasing refractive index. Lens designers use this fact to produce compound lenses, in which the dispersion of a strong positive component made from a glass of low dispersion is balanced against that of a weak negative component made from a glass of high dispersion. This combination gives a positive lens of longer focal length than the positive component itself, but with greatly reduced variation of focal length with wavelength. In the case of achromatic objectives, corrections of this type result in red and blue images being focused at the same distance. This correction is only complete for two specific wavelengths, and *residual chromatic aberration* will be shown both between and outside these wavelengths. One practical consequence of chromatic aberration becomes apparent when an image is focused visually by light of a longer wavelength than that used for producing the image (Chapter 6). This was a source of trouble to the early microphotographers,(4) who found that they had to compensate for the difference between the visual focus observed by white light, and the photographic focus of wet-collodion plates which are only sensitive to the blue and ultra-violet. The same trouble has been experienced by modern workers operating the collodion process, but was alleviated by focusing through a blue filter so that the spectral regions used for focusing and image formation are brought closer together.

Chromatic aberration is a property which has quite different effects on the image quality of photomicrographs and microphotographs. In photomicrography the plate is often required to record the whole visible spectrum in order to give a satisfactory reproduction of coloured specimens ; and chromatic aberrations can result in loss of sharpness, or actual colour fringes at the edge of the image may be recorded on dye-sensitized emulsions. A minimum of chromatic aberration is thus of real importance for photomicrography. In microphotography, however, it is usually possible to arrange that the image is formed by such a narrow band of wavelengths that slight chromatic aberration is unlikely to spoil the sharpness. In fact, the reader can regard chromatic aberration as an inconvenient property rather than as a serious defect. Little advantage is therefore to be expected from the use of expensive " Apochromats ", which are corrected to have the same focal length for at least three wavelengths.

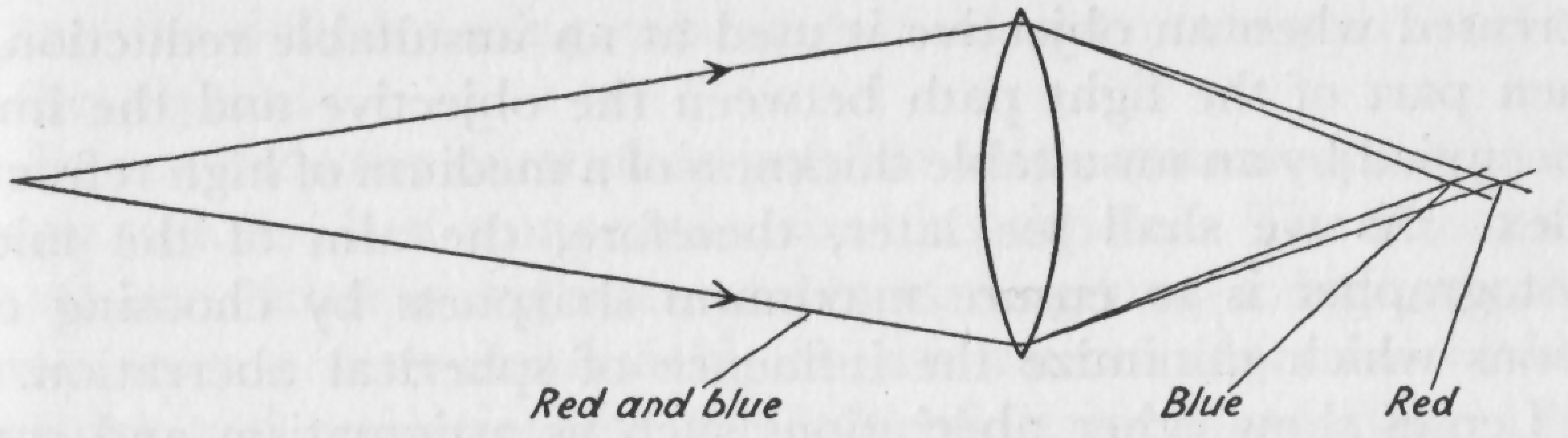
Distortion

Most objectives give an image which is not completely free from distortion. Images of rectangular rulings may be produced with lines curved, or with angles changed or with different spacings in different parts of the field. So long as these effects are not present to an immediately obvious extent they are not of serious consequence for some types of microscopic images, nor for document microphotography. Distortion is, however, of critical importance for the production of precision scales and graticules (Chapter 11). Thus at the Möller graticule factory it has been the practice to test several objectives of the same make for distortion, and only use those which survived the most rigorous examination.(5) It is, perhaps, also worth noticing that distortion is a serious problem in aerial survey (photogrammetry). If their focal length is satisfactory, lenses used for aerial survey might therefore prove suitable for some purposes in microphotography.

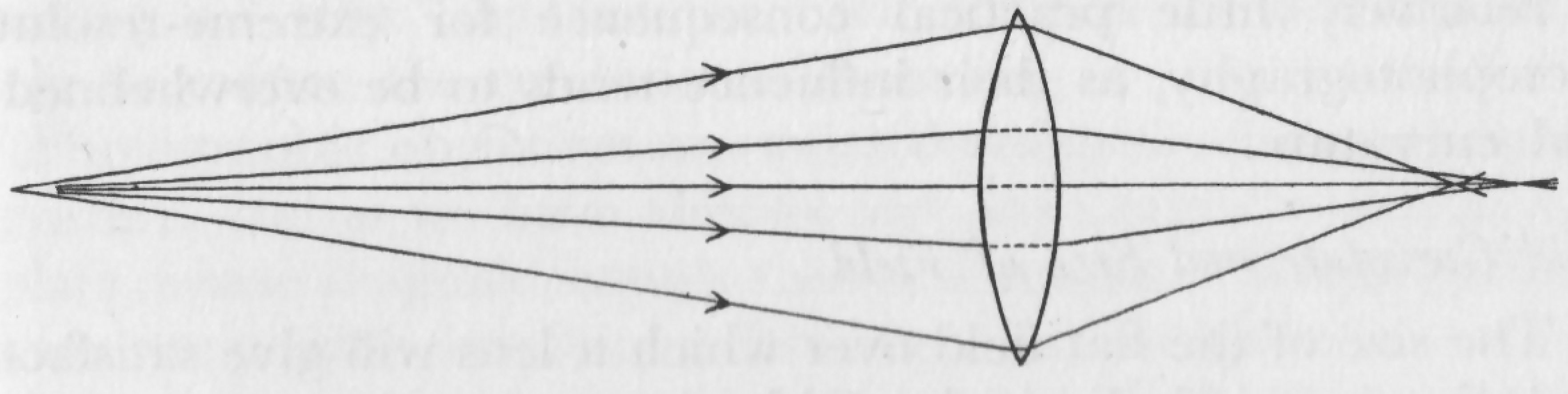
Spherical Aberration

Diagrams illustrating ideal image formation by a lens show all zones of the lens collecting light from a point on the object, and then focusing this light to form a point in the image plane (*Figure* 25). In fact, this ideal situation only occurs with so-called " perfect " objectives when both the object and the image lie close to the axis of the lens, and are situated at special positions known as the *aplanatic points*, so that a definite degree of reduction is obtained. When the degree of reduction is altered, or with practically all photographic objectives, light passing through the outer zones of the objective tends to be focused on a different plane from the focus of the central zone (*Figure* 26*b*). This defect is known as *spherical aberration*, and is of crucial importance for the sharpness of microphotographs.

Lenses are frequently classed as " perfect " or otherwise according to their spherical aberration. The perfect lenses are those designed to show a minimum of coma and of spherical aberration on the axis. They are mainly used in instruments such as microscopes or telescopes, in which the objective is used to cover a small angular field while working at a practically constant reduction. Perfect lenses are so well corrected that they can be used at full aperture without loss of resolution, and the resolution is actually decreased by stopping down. It cannot be too strongly emphasized, however, that their full resolution is only obtained quite close to the axis, so that these objectives cover a very restricted field.



(a) Chromatic Aberration



(b) Spherical Aberration

FIG. 26. *Aberrations.*

Images are formed at different distances :

(*a*) by light of different wavelengths in the case of *chromatic aberration*, and
(*b*) by light from different zones of the lens in the case of *spherical aberration.*

The objectives used in photographic cameras are, on the other hand, required to cover a much larger field and to give acceptable results at a range of reductions. The designer meets these requirements by compromises giving greater flexibility in use at the expense of some axial resolution. Photographic objectives normally show appreciable spherical aberration even on the axis, and some consequences of this have been discussed by G. H. Cook.(6) The correct focus in these objectives is defined not so much by a point but rather by the smallest disc through which rays from all zones of the lens pass. As a result of spherical aberration, photographic objectives tend to give their best resolution at one or two stops below full aperture (see below), and the position of best focus may alter as the aperture is changed. This change of focus has a detrimental effect when an objective is focused at its full aperture and is stopped down for making the exposure. Objectives intended for photomechanical work (so-called " Process " lenses) are usually designed to reduce such changes of focus to a minimum.

The spherical aberration shown by an objective is not a constant property, but changes with the conditions of use. Thus it may be increased when an objective is used at an unsuitable reduction, or when part of the light path between the objective and the image is occupied by an unsuitable thickness of a medium of high refractive index. As we shall see later, therefore, the aim of the microphotographer is to ensure maximum sharpness by choosing conditions which minimize the influence of spherical aberration.

Lenses show other aberrations such as astigmatism and coma, when the image is formed further away from the axis. These are of relatively little practical consequence for extreme-resolution microphotography, as their influence tends to be overwhelmed by field curvature.

Field Curvature and Size of Field

The size of the flat field over which a lens will give satisfactory resolution is strictly limited. Objectives normally reproduce a flat original as a saucer-shaped surface with its concave side towards the objective (*Figure* 27). The useful area of the field is then determined by the portion of this saucer whose depth is just contained within the depth of focus of the objective.

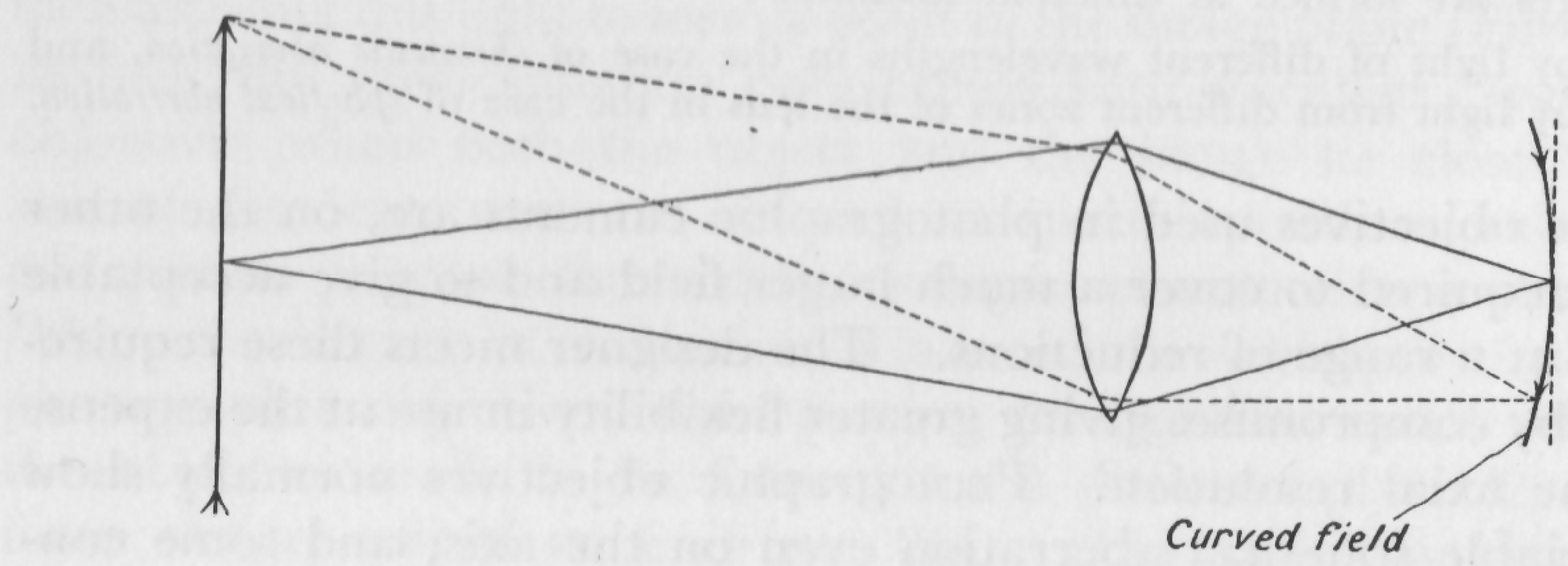


FIG. 27. *Field Curvature.*

The image of a flat original projected by an uncorrected objective often lies on a spherical surface.

In microscope objectives the diameter of the useful field is usually less than one-tenth (or even one-twentieth) of the focal length of the objective. This limitation of the area of the field has proved a serious handicap in photomicrography, and microscope manufacturers have devoted much attention to the improvement of this property. Larger useful fields can be obtained by the use of " Planochromat " objectives specially designed for this property, or by using such eyepieces as the " Periplan " or " Homal " which flatten the field by using their own field curvature to cancel that of the objective.

In any case the microphotographer using microscope objectives has to seek the best compromise for his purpose. The alternatives are to use either a high-power objective giving a high resolving power over a very small field, or else use an objective of lower aperture and resolution for the sake of its increased field. With any given objective a somewhat larger field can be obtained by inserting a " stop " against the back component, but this is also likely to reduce the resolution obtainable.

Photographic objectives are more thoroughly corrected for field curvature, and as we have already seen are normally used to cover a plate whose diagonal equals the focal length. When used with extreme-resolution emulsions, however, such objectives are only likely to give their sharpest image over a field whose diameter does not exceed one-fifth of the focal length of the objective. In this connection it is interesting to note an important difference between the properties required in objectives used for making document copies and instrument scales. In the latter application small size and portability of the reducing apparatus are much less important, so that it is practicable to employ objectives of much longer focal length, and use only the central part of the field for making the images.

The effective size of the field obtained with any objective can also be increased by arranging the image so that it tends to conceal the reduced sharpness of the outer parts of the field. Thus resolution-test images can be laid out in a spiral pattern, with the finest images in the centre of the field (see *Figure* 75). A degree of unsharpness which would spoil the smaller images may hardly be detected on the larger images at the edge of the field. It is also useful to remember that the loss of sharpness due to astigmatism in areas off the axis tends to be greater for lines running tangentially with respect to the axis, than for those running radially. Thus on moving out from the axis, " cross-wires " in a graticule image are likely to show loss of sharpness later than lines placed at right angles to them.

Resolving Power and Sharpness

The ability of an objective to give a sharp image of fine details is (for microphotography) the most important property of all. It has become customary to judge this ability by measuring the resolving power of the objective. For this purpose the objective is used to reduce a test chart (see Chapter 13), and the reduced image is either recorded photographically and subsequently examined with a microscope, or the aerial image is inspected directly with a microscope. The smallest image in which the component lines can just be separated indicates the resolving power. The measured figure indicates only the limit of resolution, and tells us little about the sharpness of larger images. The physical nature of this measurement has been explained by Selwyn and Tearle(7) in the following way. Consider the intensity distribution across the lines of a test image with lines of ever-decreasing width and separation. The objective at first reproduces the wide lines with only slight degradation ; but, with decreasing line width, the edges become rounded until the contrast of the entire image starts to decrease. The limit of resolving power is then determined by the line width at which just enough contrast remains for the image to be recognizable (see also *Figure* 55, page 167).

The resolving power of an objective is controlled by its aperture and by any aberrations which may be present. Most books on microscopy describe how the resolution depends on diffraction resulting from the wave nature of light. It has been calculated for aberration-free lenses that the minimum distance between a pair of lines which can be separated is given approximately by the expression :

$$d = \frac{\lambda}{2(\text{N.A.})}$$

where λ is the wavelength of light.

Thus the larger the aperture and the shorter the wavelength of the light used, the smaller will be the distance d, and the higher will be the resolving power. The measured axial resolution of telescope and microscope objectives is usually close to the figure given by this formula, but the axial resolution of photographic objectives is somewhat reduced by aberrations. It can often be improved by stopping down, and so cutting out the marginal zones showing the worst aberrations. The improvement obtained by the reduction of the aberrations more than compensates for any theoretical loss caused by the reduced aperture. Stopping down below F/16 or F/22, however, is not usually profitable, since diffraction causes an increasingly serious loss of resolution.

As with figures for the resolution of emulsions (Chapter 3), caution is needed in assessing the significance of the resolution figure of an objective in terms of the eventual image sharpness likely to be obtained. The observed resolving power depends not only on the properties of the lens but also on the conditions used to observe the image. This is well illustrated by a figure in Selwyn and Tearle's paper, which shows that the aperture of aero objectives giving the optimum resolution was strongly dependent on the emulsion used. Such results are due to the interplay between aberrations and diffraction. Another example was provided by Perrin and Altman,(8) who determined the connection between the measured resolving power of photographic emulsions and the apertures of the " perfect " lenses used to form the images. Eastman Kodak 548 GH plates gave figures increasing up to the highest aperture used (N.A. 0·85), whereas the resolution measured on high-speed emulsions actually decreased with apertures above 0·25. It should also be remembered that the resolution obtained with objectives showing chromatic aberration will depend on the spectral distribution given by the illuminant and the spectral sensitivity of the emulsion. Furthermore, Higgins and Jones' paper on sharpness (see Chapter 3) showed that the correlation of sharpness with resolution measurements is no better with objectives than with emulsions.(9) An instance is shown where photographs made with an objective focused to give optimum resolution are notably less sharp than others made with the focus altered by $\frac{1}{25}$ in. (1 mm.). In the former case the objective recorded a point source as a small dot surrounded by a diffuse aberration patch, and in the latter the image was a compact dot about three times the diameter of the first.

The practical lesson to be learned from these difficulties is that the low contrast of an image corresponding to the limit of resolution makes it practically useless for microphotography. Satisfactory quality is only obtained with larger images, and the way in which the image contrast changes with size is really the factor determining the useful limit of any objective.

Suitable Types of Objectives

The only objectives specifically suitable for extreme-resolution microphotography are those employed on metallurgical microscopes and used without either a cover-glass or an eyepiece. These are primarily designed for photomicrography, but are illogically named " microphotographic ". There may be no necessity for the general reader to go to the expense of acquiring objectives especially for microphotography, since a lens already in his possession may give satisfactory results. The crux of the problem is to find objectives providing both the resolution required and an adequate flat field. We have already seen that these properties are related reciprocally; the largest field being accompanied by only moderate resolution, or extreme resolution may be given over only a limited field. The present section is intended to suggest types of objective amongst which the reader might usefully search.

Photographic objectives may suffice when only moderate reductions are to be attempted. Their resolution is often described by the ratio of the " circle of confusion " to the focal length, which implies that the actual size of this circle should decrease with decreasing focal length. It is probably for this reason that Allen (10) suggested the use of objectives designed for narrow-gauge ciné work. The price of photographic objectives may give little indication of their suitability for this work. Some simple and less-costly objectives, such as portrait lenses, may be found to give excellent sharpness over a restricted field. " Petzval " portrait lenses are in particular reputed to show high axial resolution, and can be acquired (second-hand) for a modest sum. Good results should also be obtained with objectives designed for more critical photographic tasks, such as photomechanical work. " Process " objectives, for instance, tend to have less spherical aberration and should show no change of focus on stopping down. An interesting catalogue of objectives used in the Möller graticule works has been given by Bovey.(5) A few of these are listed in Table IV.

The Leitz Summar and Goertz Hypar objectives are singled out as being particularly good. The latter objective is used for making scales 5 mm. long divided into 500 divisions by 3 micron lines: a most meritorious performance. The interest of this list depends on the fact that it describes objectives which have been found suitable for the industrial production of graticules. It should, however, be noted that each lens was a specially picked individual, and thus cannot be assumed to represent the ordinary commercial

TABLE IV

Some Objectives used in the Möller Graticule Factory

Manufacturer	*Name of objective*	*Focal length*		*Aperture*
		Inches	*Mm.*	
Goertz	Artar	23½	600	F/11
Goertz	Hypar	1¼	30	F/4·5
Voigtländer	Apo-Collinear	39	1,000	F/12·5
”	Dinar	4⅔	120	F/6
”	Altin	1½	35	F/4·5
Leitz	Periplan	6	150	F/10
”	”	3½	90	F/3
”	Summar	3	80	F/4·5
Winkel	Mikroluminar	2	50	Not stated
Zeiss	Mikrotar	1¾	45	F/4·5

standard. It is possible that equally suitable objectives could be selected from lenses of similar types produced by non-German manufacturers. There are also indications that optical manufacturers are starting to develop objectives specially for this work. One example is the " Unilite " 135 mm. (5½ in.) specially designed by the firm of Wray for high-resolution work and the making of graticules.(11)

While images with a diagonal of 0·2 in. (5 mm.) or larger are conveniently made with photographic objectives, the resolution is unlikely to be satisfactory for much smaller images. Really fine lines over a restricted field are more readily obtained with microscope objectives. " Achromats ", representing the less-expensive objectives made by modern manufacturers, are corrected for spherical aberration for only one colour, usually the yellow-green. They thus give satisfactory results on the usual types of commercial concentrated-Lippmann emulsion, which have a pronounced sensitivity peak in this region of the spectrum. Chromatic aberration in achromats is normally corrected for two wavelengths, one in the blue (4,861 Å.) and the other in the red (6,563 Å.), and these objectives show small changes of focal length between these limits. They are, however, prone to show a rapid change at shorter wavelengths (violet and ultra-violet), which makes them less suitable for emulsions having most of their sensitivity in this region of the spectrum.

The more expensive " fluorite " and " apochromatic " objectives are better corrected for use with a wide band of wavelengths, but cover a smaller field and have to be used with a compensating eyepiece. It is doubtful whether they offer any substantial advantage for microphotography.

Some objectives are corrected to bring the near ultra-violet (3,650 Å.) and the green (5,460 Å.) wavelengths to the same focus, so that they can be focused visually by green light and then used for image formation on ultra-violet-sensitive emulsions. We have already noted that certain combinations of objective and eyepiece have been used to give an increased field in photomicrography, and these may also be valuable for commercial microphotography.

Testing Objectives

No two objectives have identical properties, and the stringent requirements of microphotography may reveal differences of little significance for their ordinary use. The reader, therefore, has not only to choose a suitable type, but also to select an individual objective. The importance of such a selection is indicated by the absence of precise published information on lenses for this work, and by the unusual working conditions and the critical performance required. It is, in this connection, interesting to note that Möller's graticule factory made a standard practice of obtaining a number of objectives of a given type, and subjecting them all to a rigorous inspection to select the best.(5) This was done by using the objectives to photograph an image comprising five copies of a fine grid, with one copy in the centre and the others at the corners of the field. The resulting image was closely scrutinized for resolution and image distortion.

The following sections describe tests, requiring no elaborate equipment, which the reader can use to determine the suitability of any objective for extreme-resolution work. These tests will also show the conditions giving the best image quality with any particular objective.

Examination of Image Contrast

While nothing short of actual use for producing photographic images will give a completely reliable indication of the effective resolution of an objective, a valuable preliminary opinion can be

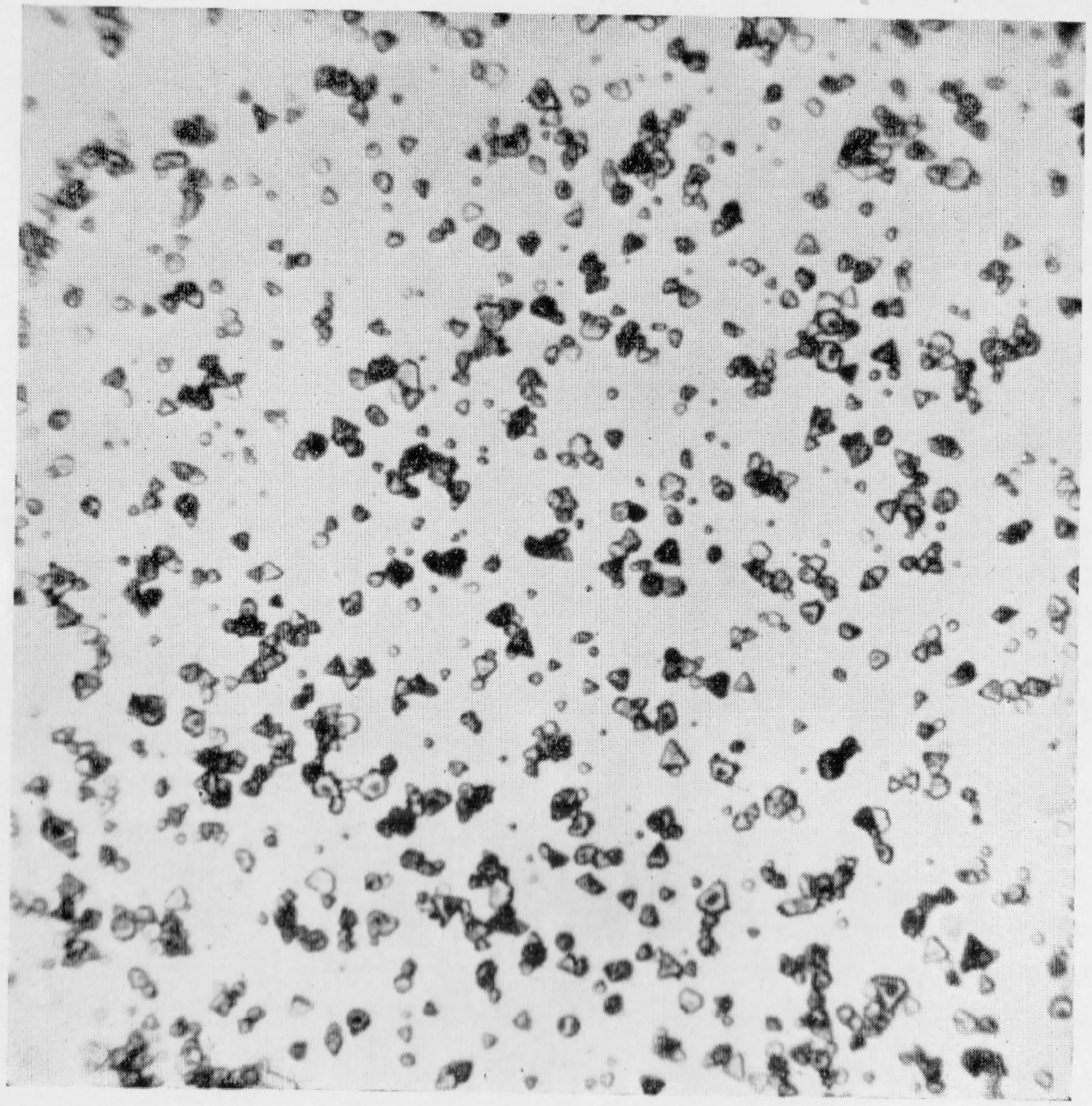


FIG. 28. *Single-grain-layer Focusing Test Plate.*

Photomicrograph (×750). Note how the field curvature of the objective is shown by decrease in sharpness at the edge of the useful field.

[*Facing p. 95.*

obtained by visual inspection of the enlarged image projected on the object plane, when a test object is placed in the image plane.

Actual measurement of resolving power by this method is not practicable, since suitable test images are not available, but the objective can be focused on an object whose structure is so fine that defects of image quality are clearly apparent. A suitable object is a single-grain layer of photographic-emulsion grains, which can be made from an undeveloped high-speed photographic plate by gently washing most of the emulsion off with hot water. It may be necessary firstly to soften the emulsion by soaking it in equal parts of concentrated nitric acid and water (*an extremely corrosive solution*). So long as the washing is done gently, and no solid is allowed to touch the surface of the plate, it will be found to have retained a very thin film of emulsion grains which provide an ideal test object for our purpose (*Figure* 28). This test object should be illuminated with a condenser or opal screen so that the objective is " filled " by the cone of light from each point of the object. The enlarged image projected by the objective is inspected with the aid of a ground-glass screen or a focusing magnifier. In the case of microscope objectives this test is particularly easy to carry out, since the objective and the test chart can be mounted on a microscope, and the sub-stage condenser is used to illuminate the test chart.

Inspection of the projected image should reveal the relative contrast and sharpness of the images of different-sized emulsion grains, and the presence of colour fringes due to chromatic aberration. The same method can be used to examine the changes in image quality resulting from changes in tube-length or aperture, or from the use of an eyepiece or cover-glass. Thus this type of test both enables a suitable objective to be chosen for use in given conditions, and shows the best working conditions for any one objective. Inspection of the changes of sharpness on moving out from the centre of the field are also easily observed, so that it can be used to show the size of the useful flat field and the position of the axis of the objective (*Figure* 42).

Assessment of the results of this test must necessarily be subjective, and depend on the judgment of the observer. The beginner may, therefore, feel bewildered and doubt his ability to derive any useful information from it, but experience has to be obtained by practice. The fortunate reader having access to several objectives of similar focal length can soon learn by comparing them with each other. Skill can also be gained by comparing the image quality on and off the axis, refocusing to obtain the greatest sharpness in each zone. It is also most instructive to compare the results given on the axis by one objective used in different conditions. Thus the image formed with a ×6 eyepiece at 10 in. (25 cm.) from the eyepiece can be compared with that produced at approximately the same magnification without an eyepiece and at a distance of 38 in. (96 cm.). The relative image quality given by each of a pair of objectives may be reversed by these changed conditions.

Visual inspection of the projected image is most likely to give a reliable estimate when the objective is to be used for the formation of images by light in the blue-green to red regions of the spectrum. Filters may then be used to ensure that the examination is made by light of a colour not far removed from that used in image formation. Such tests are not easy to make with blue light, because of the reduced visual acuity in this spectral region. For this reason the image quality of objectives to be used with blue-sensitive emulsions should preferably be recorded photographically, on a blue-sensitive plate. Photographic records of this test are in any case valuable, since they provide permanent evidence of the behaviour of each objective.

Determination of Focal Length

The focal length of objectives is seldom exactly equal to the nominal figure, and may differ from it by as much as 10 per cent. The error can be quite serious when it is desired to calculate the object distance required to give a certain image size. The focal length can be determined with something approaching the required accuracy by using the objective to make a microphotograph, or, more easily, to project an enlarged image of a stage-micrometer scale. The degree of reduction (or enlargement) and the object-to-image distance are then measured as accurately as possible and the values obtained substituted in the formula :

$$f = \frac{D \times R}{(R+1)^2}$$

where D equals the object-to-image distance
and R equals the degree of reduction (or enlargement).

With increasing values of R this formula approximates more and more closely to the simplified form :

$$f = \frac{D}{R+2}$$

In fact, with degrees of reduction of 20 or more the error due to the use of the approximate formula is likely to be less than the experimental errors in determining D and R.

When focal lengths are determined in this way, the figures obtained should enable any desired image size to be obtained with an accuracy of about 1 per cent. by direct calculation. It is a good plan to measure the degree of reduction each time an objective is used and tabulate the data for future use, and possibly also plot the measured degrees of reduction against the object-to-image distance. This should enable the required image size to be obtained with even greater accuracy on future occasions.

Method of Use

We have, in this chapter, discussed a number of ways in which the performance of objectives departs from the ideal. The effect of these deficiencies can be kept to a minimum by selecting the best conditions for high resolution. This is done mainly by avoiding conditions which tend to increase the aberrations shown by the objective.

Direction of Objective

Among opticians it is common knowledge that an optical system can only be completely corrected for one object distance. This means that the greatest freedom from aberrations, and hence the sharpest image, will only be obtained at one degree of reduction which is fixed for each objective. With most lenses this degree of reduction is usually at least 4, and is often much greater. The conjugate points for these conditions are thus at unequal distances from the objective. In addition most lens designs have no symmetry about a plane at right angles to the axis, and will only give their best results when facing the correct way. In other words, most lenses are designed to be used with unequal conjugate foci, and it is most important to ensure that the correct end of the objective faces the nearer conjugate focus (usually the emulsion).

This rule must be observed whatever the direction in which the objective is customarily used. Thus microscope objectives are normally employed to form an enlarged image of a small object, and the R.M.S. thread (see *Figure* 41) points towards the large image. When used for microphotography the thread must still point towards the further conjugate focus. It is immaterial that a large object is now placed there, and that a reduced image is formed at the nearer focus. Similarly the short focal-length objectives used with narrow-gauge ciné cameras are used with the engraved side of the mount facing the further conjugate focus, while the thread faces the emulsion. If used for microphotography they must be mounted so that the engraved side points up the microscope tube, and thus faces the original placed at the further conjugate focus.

Degree of Reduction. Theoretical Requirements

Although the best resolution given by any objective is in theory obtained at one definite degree of reduction, some departure from this figure may in practice give satisfactory results. Thus a 6-in. (15-cm.) objective in a hand camera might give very similar sharpness when focused at any distance from 25 ft. to infinity, but could be expected to display a less sharp image when used at less than 6 ft., i.e. with reductions of less than ten diameters. Enlarging and photomechanical " process " lenses, on the other hand, are generally computed to give their best results with reductions between two and ten diameters, but may show inferior resolution if used outside this range.

The high aperture and more exact corrections of microscope objectives makes them more sensitive to any departure from the optimum conditions. In fact, an objective should ideally be used at only one magnification, normally corresponding to the formation of the primary enlarged image at the end of a tube of length 6½ in. (160 mm.). Moreover, most microscope objectives are designed for the inspection of specimens mounted under a cover-glass. Appreciable departure from either of these conditions introduces spherical aberration. Martin and Johnson (12) show how spherical aberration can be recognized by the uneven appearance of the patches of light formed by projecting an enlarged image of a " pinhole " in a silver mirror, and adjusting the focus to positions slightly inside or outside the correct focus.

Degree of Reduction tolerable in Practice

The production of the primary image at a distance of 6½ in., as demanded by orthodox microscopic practice, is somewhat inconvenient for microphotography, since it involves small degrees of reduction and the consequent use of small originals. Thus if a 1-in. (25-mm.) objective is required to make an image 1 mm. high, the reduction at 6½ in. will only be about six diameters, and the original must be only ¼ in. (6 mm.) high. Such an original is too small for convenience, since exceptional care would be needed to produce the perfection desirable in an intermediate transparency for microphotography (Chapter 8).

Experience has shown that surprisingly good resolution can be obtained with suitably-chosen microscope objectives used at distances at least up to 39 in. (1 metre). The image quality given by low-power objectives of focal length greater than ½ in. (12 mm.) does not seem to suffer appreciable degradation from the use of these " incorrect " conditions. The author has even obtained images resolving more than 1,500 lines per millimetre by using a ⅙-in. (4-mm.) achromatic objective of N.A. 0·85 at a distance of 26 in. (65 cm.). This excellent performance under " incorrect " conditions is probably due to two facts. Martin and Johnson (12) point out that longer tube lengths may be used to compensate for the absence of a cover-glass. In fact, the error due to excessive working distance is at least partly compensated by the absence of a cover-glass. Moreover, the objective was an individual specimen specially chosen for use with these greater distances. Microscope objectives are still largely hand-made articles and no two individuals have identical properties. Some must therefore be better suited than others for use in unusual conditions.

If the reader does decide to use an available objective under unorthodox conditions, it is particularly important to examine the quality of the projected image by the method already described. For instance, it was found that a pair of 4-mm. objectives by the same reputable manufacturer gave quite different results. Both gave excellent images when used correctly, but only one produced a satisfactory image at a long working distance and without an eyepiece or cover-glass.

Use of an Eyepiece

We have, so far, assumed that the microscope objective will be used without an eyepiece. The arguments for using or omitting an eyepiece have not yet been resolved. The length of bench required for a given reduction, for instance, is substantially lessened with an eyepiece, and field-flattening eyepieces enable a larger field to be covered with an image containing lines of a given width. On the other hand, eyepieces contain glass surfaces which are so close to the longer conjugate focus of the objective that even minute particles of dirt in the eyepiece may cause a blemish in the image. They also complicate the precise calculation of the working distance needed to obtain a given image size.

Adjustment of Aperture

The performance of all objectives is influenced by the aperture at which they are used. With photographic objectives " stopping down " usually lessens aberration and at first gives increased resolution. The best result is usually given by an aperture between 1 and 3 stops (on the " F " scale) smaller than the maximum. To guard against changes of focus resulting from spherical aberration (see above), objectives used for extreme-resolution work should always be focused at the aperture used for actual image formation. This differs from the common photographic practice of focusing at full aperture, and stopping down before exposure.

Appreciable stopping down of correctly-used microscope objectives should always result in a loss of resolution ; but a small reduction of aperture may improve the image by reducing the intensity of the flare light. Reduction of the aperture may also be used to increase the area of the useful field obtainable with any objective, at the expense of some loss of resolution. Few microscope objectives are fitted with an iris diaphragm, but their aperture can be reduced by placing a disc of black paper with a hole of suitable size on top of the back component of the objective.

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CHAPTER 6

Establishment and Maintenance of Focus

One of the essential problems to be solved when making microphotographs is that of establishing and maintaining the exact focus. Methods which are normally used successfully, even in such an exacting field as " miniature " photography, are of comparatively little use. The difficulty can be readily understood, when one realizes that the " circle of confusion " which has to be specified for microphotography is necessarily much smaller than that required for any other type of photographic work. Let us take a numerical example. With a camera lens of focal length 2 in. (50 mm.), a circle of confusion of one two-thousandth of the focal length (i.e. 0·001 in. or 25 μ) would be considered reasonably satisfactory. This is equivalent to a resolution figure of not more than 40 lines/mm., and the high turbidity of the " negative " emulsions normally used with the lens will tend to conceal its ability to give greater resolution. With an extreme-resolution emulsion, however, a good miniature-camera should be found to give an axial resolution of about 300 lines/mm. This is equivalent to a circle of confusion about eight times smaller than the previous figure. A number of practical consequences can be deduced from this example :

(*a*) The depth of focus at the emulsion surface will necessarily be much shallower than when the same lens is used with less critical emulsions.

(*b*) The structure of even the finest ground-glass screen is so coarse that it can only be employed for making preliminary rough adjustments.

(*c*) The registration by which the emulsion can be repeatedly located in a predetermined plane has to be effected with great precision.

The problem of ensuring sharp focus can be conveniently divided into the optical problem of establishing focus and the mechanical

problem of maintaining it. Several solutions of each problem are available. The matter is so vital for this work that no apology need be made for describing these methods, and their merits, in some detail.

Establishing Focus

The *focus* (or plane of sharpest image formation) should be placed at or just below the emulsion surface (Chapter 9). This adjustment can only be made with certainty when sufficiently sensitive means are used both for observing the results of focusing adjustments, and for moving the plane of the aerial image relative to the emulsion layer.

Direct Visual Observation of the Focusing Operation

An easy and convenient method of observing the focusing operation in normal photography is to employ a ground-glass screen in which one side of a glass plate is covered with innumerable glass pits. These scatter the light falling on them so that the screen appears as if it were self-luminous, and the image formed by the lens seems to reside in the screen itself.

Ground-glass screens are satisfactory for the focusing of images which are to be magnified only a few times, but their structure is too coarse for images which may be viewed at high magnifications. In such cases visual focusing may be effected by placing a layer containing fine detail in the image plane, and using the details to fix the focus of the eyes. According to the precise method used, the fine detail may consist of dirt on a slightly unclean glass plate, or a plate bearing a single layer of grains from a high-speed emulsion (*Figure* 28), or the microphotographic emulsion layer itself, which can be made more visible by ink marks or slight scratches.

Visual focusing can be performed in several ways. If the microphotographic camera is not equipped with accurate means for locating the emulsion surface, the objective must be refocused on each plate used. In this case the image plane has generally to be located by viewing marks in the surface of the emulsion on each plate, and this is usually done with an orange or red filter to reduce fogging. With apparatus giving accurate registration any flat and rigid surface will take up the same position, and it is therefore no longer necessary for the fine detail to be contained by the sensitive plate. Other surfaces, such as the single layer of grains, can be used for focusing and plenty of light may be used without risk of fogging the plates. Whatever type of layer is used to fix the focus of the eyes, an effective method must be used to magnify the fine detail so that focusing can be accomplished with the necessary accuracy.

Observation through the Back of the Plate

A microscope directed at the back of the plate may be used to observe the focusing operation. For this purpose the aperture of the viewing objective must be at least as great as that of the image-forming objective. If it is smaller the focusing operation will be uncritical and less able to allow for any residual aberrations in the image-forming objective (*Figure* 29). It is also desirable to employ a magnification rather greater than that likely to be used for inspecting the final microphotographs, so that small errors of focusing are unlikely to show in the final result.

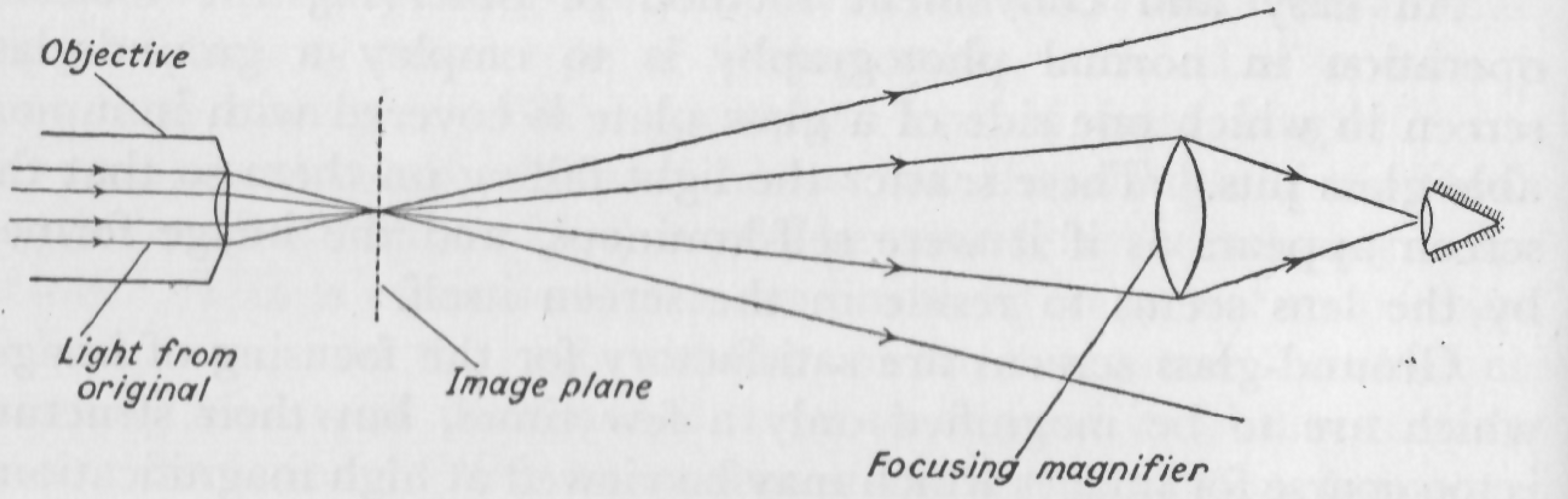


FIG. 29. *Visual Focusing at the Image Plane.*

The magnifier shown will only accept light from the central zones of the objective, and focusing will tend to be inaccurate.

The viewing microscope must be held quite rigidly and steady relative to the image plane. For this reason the use of a separate microscope involves some elaboration of the apparatus, and may only prove profitable in large-scale commercial work. The Möller graticule factory, for instance, employed focusing microscopes not only for focusing but for checking the size of the reduced aerial images as well.(1)

A simpler method, described by Shadbolt as early as 1857, is to mount the image-forming objective in the condenser holder of a microscope, and lay the emulsion-coated plate face downwards on the stage.(2) The ordinary objective and eyepiece of the same microscope is then used to examine the focus. This method should allow the owner of a microscope to commence making microphotographs with a minimum of preparation, so long as the microphotographic objective is aligned and centred with sufficient care.

The Technique of Visual Focusing

Although visual focusing is not intrinsically difficult, the accuracy will be seriously reduced if the focus of the eyes is allowed to jump alternately between the emulsion surface and the aerial image. The following technique should, with a little practice, overcome this difficulty :

(i) First use the viewing microscope to locate a focusing mark on the plate, and bring it near the centre of the field. The mark should contain detail requiring critical focusing of the eyes, but must leave sufficient of the field clear to permit observation of the reduced aerial image.
(ii) Next throw the microphotographic objective deliberately out of focus, so that the light it transmits merely serves to illuminate the plate. Confirm that the viewing microscope is comfortably focused on the mark. The plane on which the attention of the eyes is concentrated should be determined only by the position of the plate surface.
(iii) Adjust the microphotographic objective until the aerial image appears sharp, in the meantime keeping the eyes focused on the emulsion surface. The focus should now be correct.

An alternative method is to proceed as above, and when both the image and emulsion surface can be clearly seen, move the eye a small distance sideways. The focus is correctly adjusted when there is no apparent movement of the aerial image relative to the emulsion surface. This method, known as " focusing by parallax ", is frequently described in works on optics and photomicrography. In the author's experience it is no more accurate and definitely more tiring than the procedure described above. It also has the additional disadvantage that small relative movements of the images may be caused by errors in the optical system, and these will confuse and lessen the sensitivity of the parallax test for correct focus.

Observation from the Front of the Plate

The use of a separate microscope for inspecting the emulsion surface is by no means essential. Most optical systems are reversible, and the objective used to form the minute images can also be used to project an enlarged image of the emulsion surface back on the object plane (*Figure* 30). When this enlarged image is in focus at the object plane, the object plane will in turn be correctly focused at the emulsion surface. With this method the dimensions of the image to be observed are much greater, so that any normal method for observing focus may be used. The depth of field at the object plane is relatively great, particularly when the shorter focal length objectives are used (see Appendix II, C). The image must therefore be watched very closely to reveal the small changes of sharpness or contrast which serve to indicate the optimum focus.

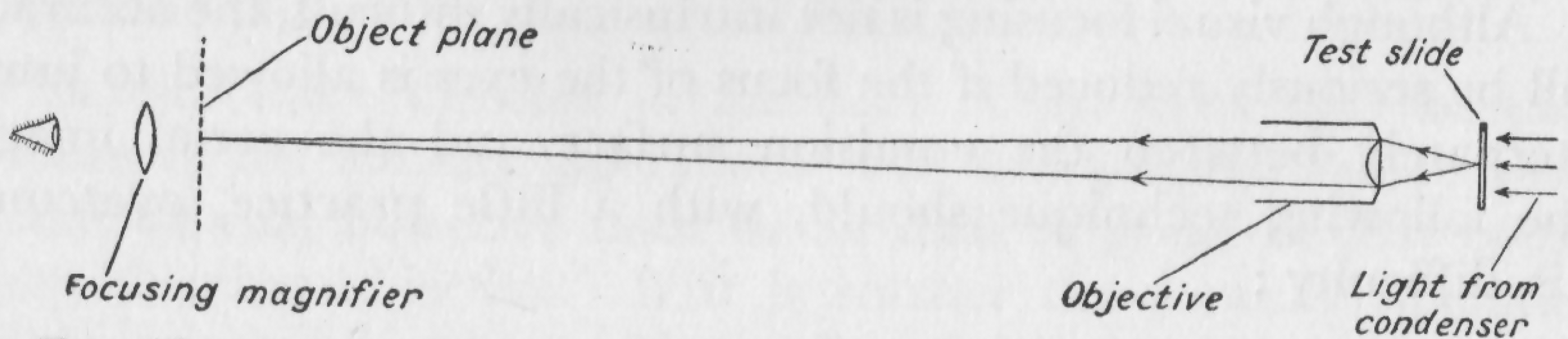
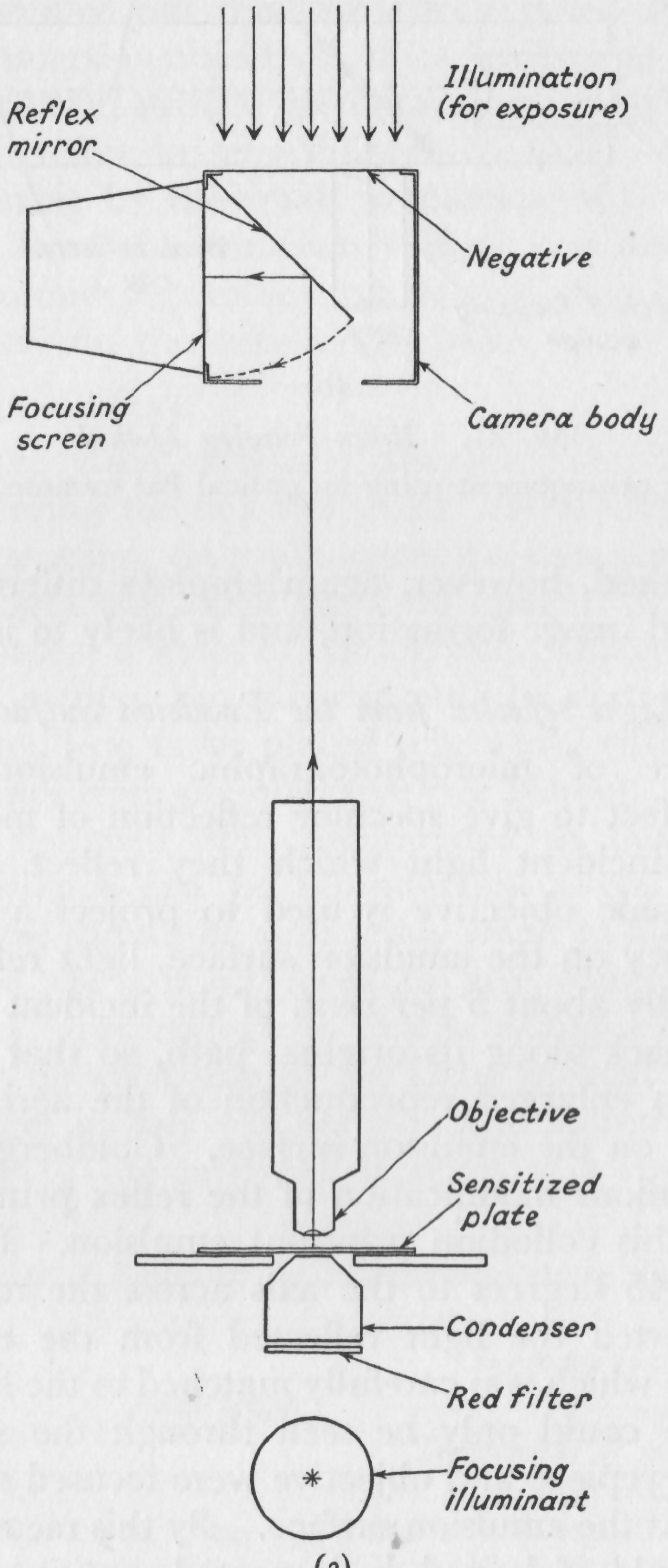


FIG. 30. *Focusing by projecting the Image Plane back on the Object Plane.*

The principle of the reflex camera can be used to facilitate this focusing method. For this purpose we may use either the body of a reflex camera (*Figure* 31*a*) or a photomicrographic side-tube reflex attachment. In either case the original is mounted in the plane which would normally be occupied by the photographic plate. The focus may then be inspected before each exposure, without the inconvenience of removing the original from its mounting. In addition the reflex principle usually allows the ground-glass screen to be viewed in greater comfort and should thereby contribute to improved accuracy.

In all these visual methods, focusing should so far as possible be effected with light of the colour to be used for image formation. Residual chromatic aberration of the objective may otherwise cause a significant separation between the planes of visual and photographic focus (see Chapter 5).

When visual focusing is made with a sensitive plate placed in the image plane, the emulsion must either be moved before exposure to bring a fresh area underneath the objective, or the light used for focusing must be filtered to remove the actinic wavelengths.



(a)

FIG. 31. *Reflex Focusing Method.*

(*a*) Use of the body of a reflex camera to hold the negative and focusing screen.

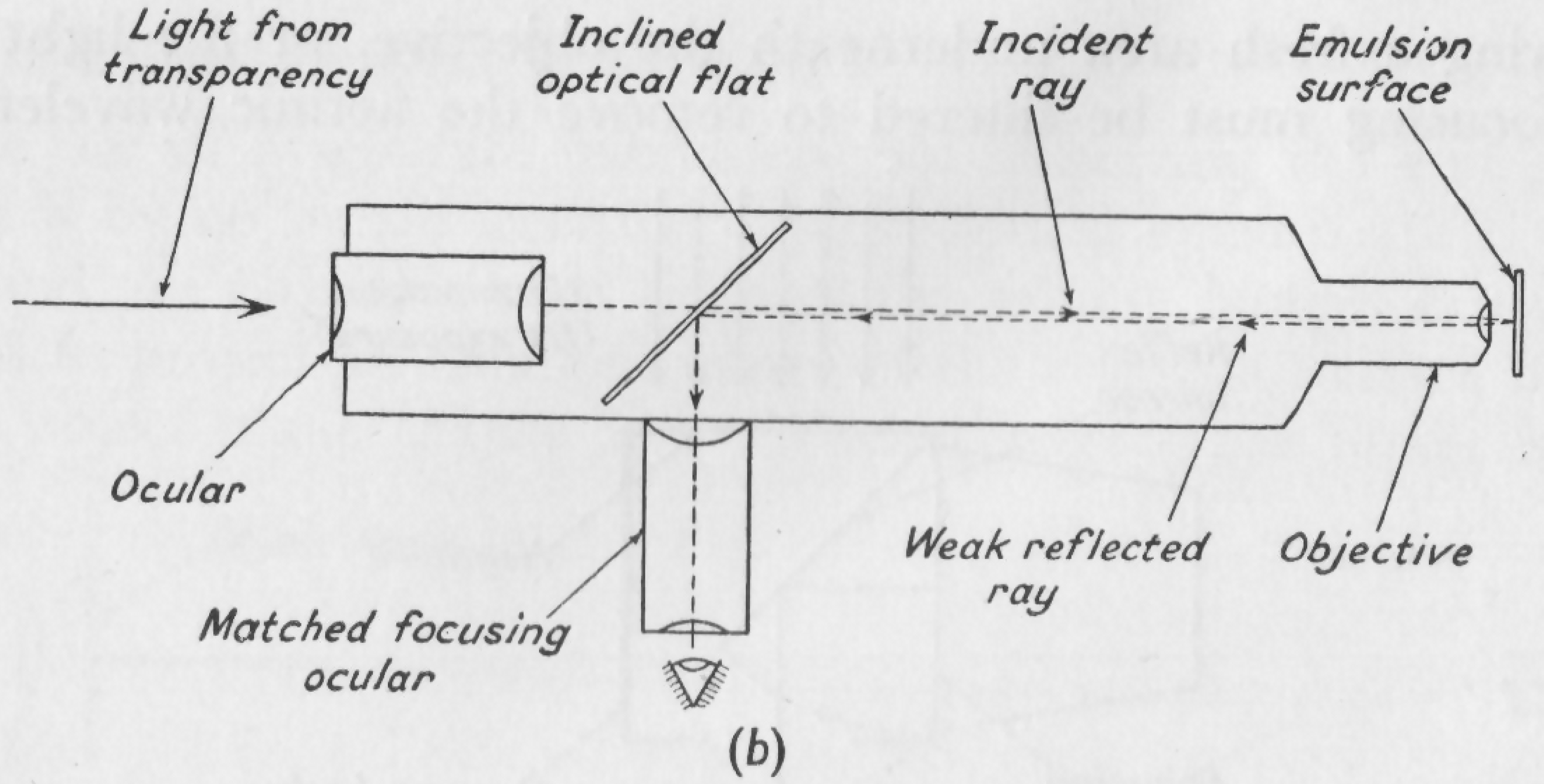


Fig. 31. *Reflex Focusing Method.*

(*b*) Goldberg's arrangement using an optical flat mounted across the microscope tube.

This latter method, however, again employs different wavelengths for focusing and image formation, and is likely to introduce errors.

Observation by Light reflected from the Emulsion Surface

The surface of microphotographic emulsions is normally sufficiently perfect to give specular reflection of most of the small proportion of incident light which they reflect. Thus when a microphotographic objective is used to project a reduced image of a transparency on the emulsion surface, light reflected from the emulsion (usually about 5 per cent. of the incident light) will tend to be turned back along its original path, so that it forms in the object plane an enlarged reproduction of the aerial image previously projected on the emulsion surface. Goldberg (3) utilized this fact in an ingenious modification of the reflex principle, which he operated with his collodion print-out emulsion. He mounted an optical flat at 45 degrees to the axis across the microscope tube, so that it diverted the light reflected from the emulsion into a second eyepiece which was carefully matched to the first (*Figure* 31*b*). A sharp image could only be seen through the second eyepiece when the first eyepiece and objective were focused so as to produce a sharp image at the emulsion surface. By this means the sharpness of the image could, if desired, be inspected continuously throughout the duration of an exposure. In addition, the print-out emulsion formed a fully visible image without development, so that its density could be inspected at any stage by interrupting the exposure and

using the condenser of the microscope to illuminate the emulsion with red light.

Goldberg pointed out that this system could not be used with oil- or water-immersion objectives, since insufficient reflection would occur at an emulsion surface in contact with these liquids, and no image would therefore be seen through the viewing eyepiece. The method of focusing by the small proportion of the image-forming light reflected from the emulsion surface can also be used with split-beam photomicrographic cameras of the type which are mounted directly on the tube of the microscope.

Photographic-focusing Tests

Although the visual methods described above provide direct means for observing the changes in the aerial image produced by the focusing operation, only photographic tests can show precisely how these changes will affect the final image. The most reliable method is to inspect a series of photographic images produced with different focus settings, but this can only be done with equipment allowing the emulsion to be placed repeatedly with great precision at a fixed distance from the objective (see below). The equipment must also be designed and manipulated so that the emulsion-to-objective distance can be reproducibly altered by very small amounts. These should be sufficiently small to allow two or three settings around the correct focus to give almost equally sharp images, but yet large enough to enable changes of image quality to be observed on each side of the focus without having to make too many images in any one series. The increments of distance shown in Table V are intended to serve as a rough guide.

TABLE V

Size of Increments for Photographic-focusing Tests

Objective	*Focal length*	*Suggested focusing increment*	
		Thousandths of an inch	*Microns*
Photographic	4 in. (100 mm.)	1·0	25
,,	2 in. (50 mm.)	0·5	12
Microscopic	2 in. (50 mm.)	0·5–0·25	12–6
,,	1 in. (25 mm.)	0·2–0·1	5–2
,,	⅙ in. (4 mm.)	0·2–0·04	5–1

It is important that the photographic test should contain a sufficient range of settings to ensure that definite deterioration can be detected on each side of the correct focus. A series of images in which the sharpness continues to improve right up to the last image cannot indicate with certainty whether optimum sharpness has in fact been achieved. With the increments suggested above a series of from five to ten images should prove adequate.

A photographic-focusing test made in this way provides a permanent record not only of the position of sharpest focus but also of the variation on each side. It is thus possible to set the focus to the position giving the greatest working latitude. In addition, it shows how the effective field covered can be influenced by the focus, and is particularly useful in cases where the covering power of the objective is barely sufficient. Careful study of a focusing test may permit the selection of a compromise setting effectively covering a slightly larger field. Examination of focusing tests also enables the operator to visualize the consequences of any adjustments made. They are thus an invaluable aid to the improvement of microphotographic technique.

Application of Visual and Photographic Observations

It should not be thought that the visual and photographic methods for observing the focusing operation are mutually exclusive. The visual method depends largely on personal skill, and may with sufficient practice be found to give perfectly satisfactory results. It is also quick and will save much time if used to obtain a provisional adjustment before making a photographic test. The latter, on the other hand, substitutes methodical operation for personal skill and is always desirable for the final stages of focusing when absolute certainty is required. Photographic focusing becomes increasingly desirable when working tolerances are reduced by the fineness of the image or the size of the field to be covered.

Adjustment of Focus

The present chapter has, so far, dealt with the methods used for observing the focusing operation, since without such observation the finest microphotographic camera would be of little use. We must now consider how the actual focusing operation should be performed.

Exact focusing in most optical instruments depends on the ability

to make very small adjustments of the distance between the objective and the image plane in a controllable and reproducible manner. Thus in microscopes much attention has been given to the design of fine-focusing mechanisms giving small movements very smoothly. In our case, however, the problem is in some ways more difficult, since the ultimate success of the focusing operation can only be judged when the microphotographs themselves are inspected ; whereas with visual use of a microscope, changes in image quality resulting from focusing are immediately apparent.

In microphotography the adjustment of the focus can be made directly by altering the emulsion-to-objective distance, or indirectly by moving the original to or from the camera. The variations of emulsion-to-objective distance need to be so small that the direct method can only be used with apparatus having a good micrometer-focusing movement. In contrast to this, relatively large alterations in the distance from the original to the camera can, as Nicholls showed in 1860, easily give the precision needed.(4) The table in Appendix II, A shows how minute are the changes in emulsion-to-objective distance following quite substantial changes in the distance of the original. The success of this method depends on the fact that, for small movements of the original, *the change in the image-to-objective distance equals the movement of the original divided by the square of the degree of reduction.* This is a very useful relationship to remember, since it allows approximate changes in the image-to-objective distance, produced by small changes in the distance of the original, to be calculated readily.

When only an insensitive focusing mechanism is available on the camera, it may sometimes be convenient to use it for preliminary focusing, and for adjusting the image to approximately the correct size. The correct focus can then be found by changing the distance of the original. This method is not suitable when images have to be made exactly to size, since the final focusing operation will also alter the image size.

Maintenance of Focus

Although some workers may prefer to adjust the focus visually just before each exposure, this can only be done at all conveniently if a reflex-focusing device is used. This method is even then somewhat wasteful of effort and time. It is generally more satisfactory to construct apparatus which will maintain the focus within fine limits, so that many exposures can be made without readjustment of the instrument. Although the permissible tolerances are small, correct design allows accurate results to be obtained with simple, and sometimes even crude, equipment.

The reader wishing either to make large numbers of images, or to explore the potentialities of microphotography to the limit, should obtain apparatus capable :

(*a*) of locating the emulsion surface in a given plane with a precision of at least 2 microns (0·00008 in.),

and

(*b*) of allowing reproducible variations of the emulsion-to-objective distance to be made in increments of 10 microns (0·0004 in.) or even 1 micron (0·00004 in.).

To meet these specifications it is necessary to consider such factors as the lack of flatness of glass plates, and the influences of dust, thermal expansion and the bending of apparently rigid structures under quite small loads.(5) In spite of these formidable requirements, the following sections will show how the necessary performance can be simply obtained by adapting existing equipment or construction of special apparatus. The important thing to notice is that the necessary precision is obtained more by attention to certain critical factors in the design, than by demanding exceptional skill from the constructor.

The Limitations of Ordinary Photographic Cameras

While fairly fine images can be obtained by the careful use of ordinary photographic equipment, the reader should realize that extreme-resolution work demands a standard of precision for which conventional cameras are never designed. Such precision would, in fact, be largely wasted on the relatively low-resolution high-speed emulsions normally used in such cameras.

Our special requirements may show that the rigidity of folding cameras is unsatisfactory, particularly if the camera has been worn by much use. Difficulty from this source can be minimized by leaving the camera open throughout any one set of exposures. Care should also be taken to avoid shifting the camera-front while adjusting the diaphragm or setting the shutter. With plate cameras the registration between the focusing screen and the plate-holders, and even between successive plate-holders, may be none too accurate. An obvious precaution is therefore to use a single plate-holder for all photographic-focusing tests as well as for making the final exposures. Moreover, the objective normally fitted will only be found to cover a small area in the centre of the plate with the perfection needed for extreme-resolution work. The important part of the image is thus formed well away from the edges of the plate, where the emulsion surface is usually registered. Lack of flatness of photographic glass plates can, in these conditions, cause a random variation in sharpness. This trouble has been avoided with the wet-collodion process by coating the emulsion on plate glass, and stripping the processed images for transfer to their final support.(6)

The use of flexible film instead of glass plates introduces further difficulties caused by bending and buckling of the film. The cure is to fix extra registration supports in the camera, so that the film is supported as close as possible around the region of image formation.

Another difficulty in using conventional cameras lies in the relative coarseness of both the focusing movement, and of the scale indicating focusing movements. Increased accuracy can be obtained by fitting a finer scale, but it is probably better only to use the camera mechanism for coarse focusing, and then effect fine focusing by altering the object distance, as already described.

Specially-designed Apparatus

In the following sections we shall consider apparatus which has been designed to overcome these limitations. It is not difficult to make equipment whereby the emulsion surface can be repeatedly located in a fixed plane relative to the objective with a precision of plus or minus a micron. All forms of such apparatus can be diagrammatically described by *Figure* 32. The plane of focus is fixed by a *contact surface* situated as close as possible to the axis of the objective. The emulsion is pressed against this surface by a force ideally acting only opposite the contact surface. This basic arrangement is suitable for obtaining both rapid working and extreme precision. One overriding advantage is that it permits uncontrolled variations of register to be eliminated almost completely. Thus when determining the best conditions for making

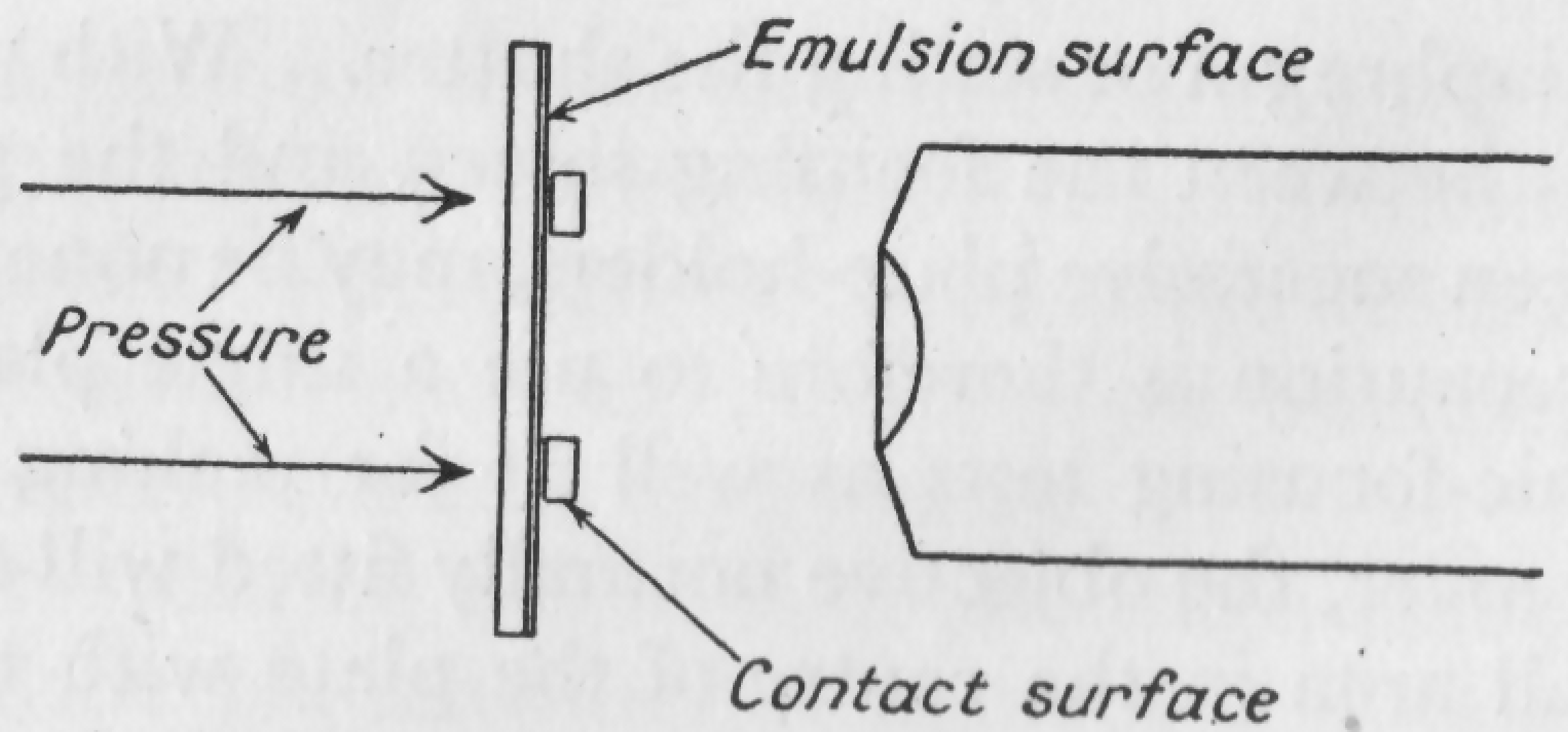


Fig. 32. *Basic Method for Accurate Location of Emulsion Surface.*

an image, variations of image quality are likely to be due to differences in emulsion properties or exposure level or development, but the interpretation of the results cannot be confused by random and unexpected changes of focus.

The following points should be considered when working out details in the design of apparatus of this general form:

(1) The contact surfaces should be located as close as practicable to the site of image formation. *Figure* 33 shows how this minimizes errors due to lack of flatness in the emulsion support, whether it be glass or film. With objectives having several millimetres' working distance between the objective and the emulsion, the contact surface can be brought very close to the image. In other cases, where the working distance is too small to admit the structure supporting the contact surfaces, a space has to be left between the surfaces

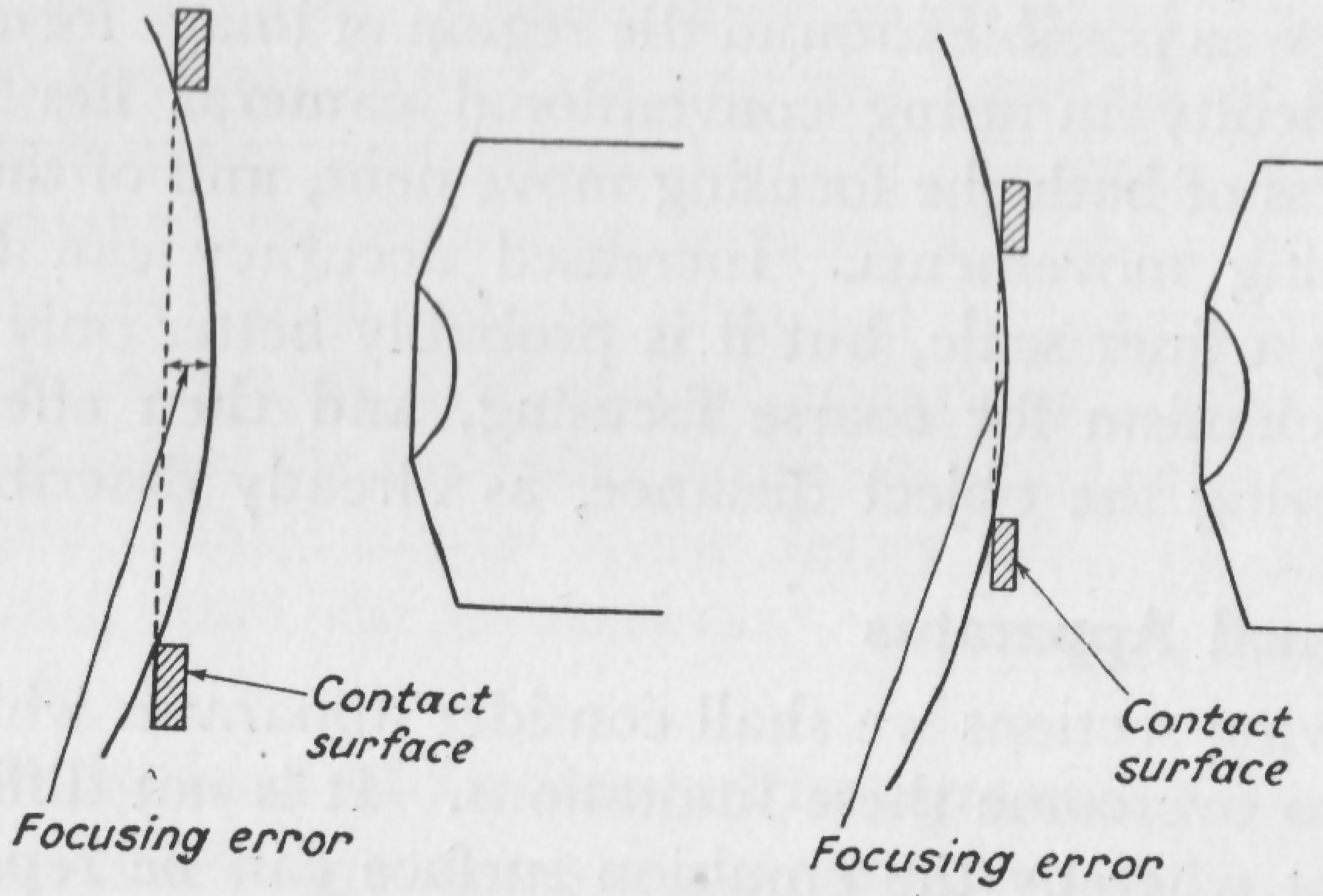


Fig. 33. *Spacing of Contact Surfaces.*

The closer are the contact surfaces to the point of image formation, the less will be the focusing error produced by curvature of the emulsion.

to allow the objective to be brought sufficiently close to the emulsion. This is, unfortunately, mainly necessary with high-power objectives, with which the greatest precision of focus is needed.

(2) The contact surfaces should be large enough to prevent serious damage to the emulsion surface (i.e. they should not be " pin-points "), but if too large will unnecessarily increase the danger of trapping dust. Either a small circle close to the axis of the objective, or three small surfaces equidistant from the axis and spaced at 120°, are convenient arrangements. The edges should be rounded so that the emulsion is not scratched when the sensitive material is moved laterally.

(3) The structure supporting the contact surfaces, and hence determining its distance from the objective, must be sufficiently rigid to prevent appreciable distortion when the emulsion is pressed against the surfaces.

(4) The sensitive material has to be supported so that the plates can be moved laterally in order to bring any desired area of the emulsion surface opposite the objective. This has to be done in such a way that the plate is still quite free to move up against the contact surfaces. If this movement is not perfectly free, the plate (or other support) may be held back, so that the emulsion surface is able to touch only one side of the contact surface. This can cause much trouble, and since failure to satisfy this requirement can lead to perplexing variations of image sharpness, it merits particularly careful attention.

(5) Sufficient pressure must be applied to the back of the sensitive material to ensure that the emulsion is always brought right up against the contact surfaces; but the pressure should be applied, as far as possible, only opposite the contact surfaces so that it does not tend to bend the emulsion support. It cannot, moreover, be assumed that even apparently rigid structures will not bend to some extent, and excessive pressure should therefore be avoided. Reproducible pressure, such as that exerted by a spring which is always compressed to the same extent, will ensure that any bending which does occur is consistent, and will not lead to random variations of focus.

(6) The emulsion should be kept away from the contact surfaces when the plate is moved laterally between exposures, or on insertion of a new plate. This precaution lessens the risk of the focus being changed by debris from the emulsion surface building up on the contact surface, and also prevents damage to both the contact surfaces and the emulsion.

These important conditions can be satisfied more by attention to details than by the use of elaborate designs. A description of some actual working systems will show how these principles can be put into practice.

Distance Pieces giving a Fixed Emulsion-to-objective Separation

Goldberg fitted a microscope objective with an accurately made tube of such a length that an object at a fixed distance was brought into focus when the emulsion was pressed against the contact surface on the lower end of the tube.[(3)] Such tubes are known as *distance pieces*, and represent a simple and effective means for converting any microscope into a microphotographic camera.

The end of the tube facing the objective has to be located against some suitable reference surface on the outside of the objective mount: fortunately most objectives bear a flange conveniently placed for this purpose (*Figure* 34). It is clear that the distance piece can only give precise location of the emulsion surface, if its

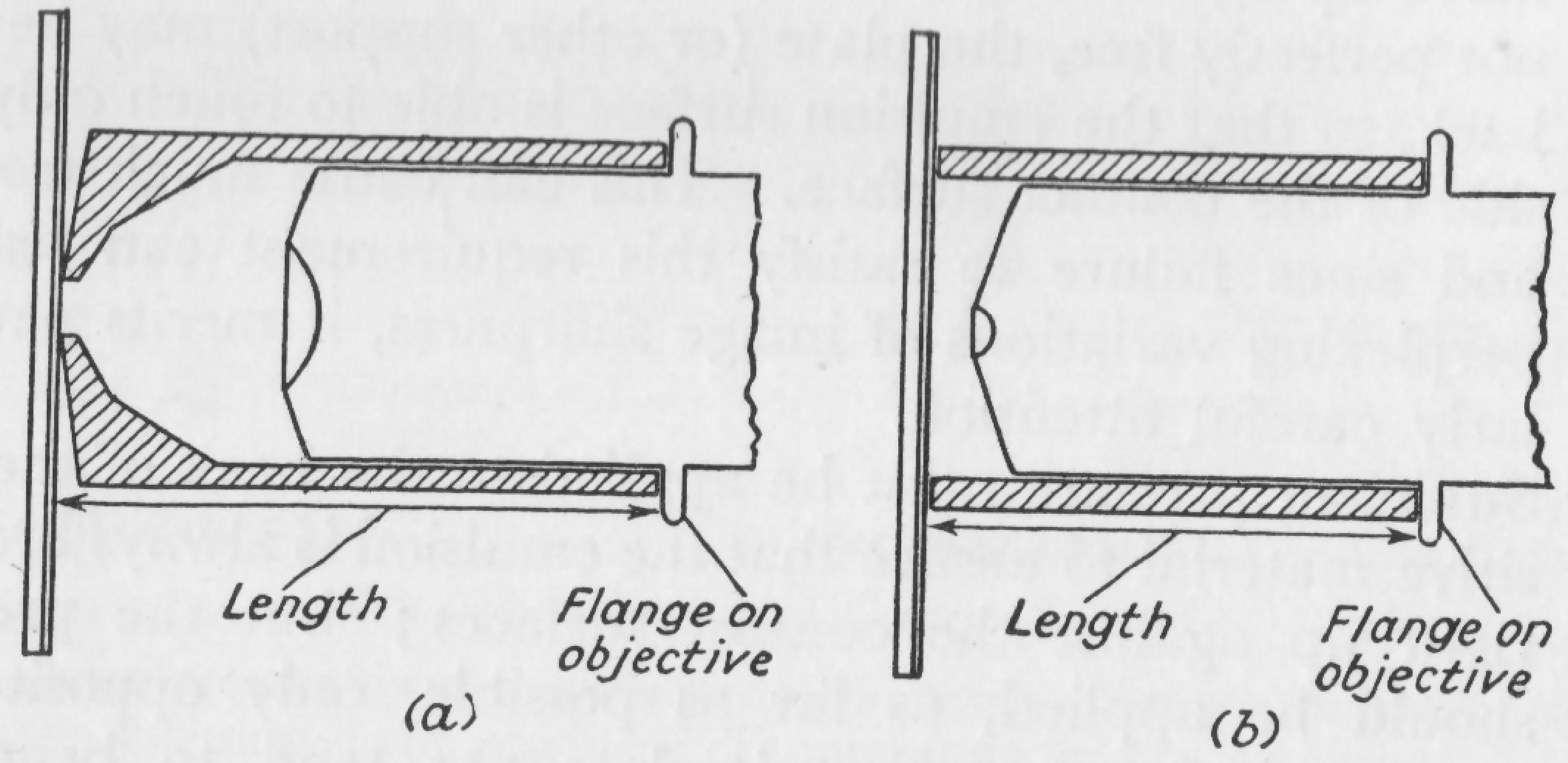


Fig. 34. *Designs for Distance Pieces.*

(*a*) " Salt-cellar " distance piece for medium-power objectives with adequate working distances.

(*b*) Tubular construction necessitated by small working distance of high-power objectives.

top surface and the flange on the objective are kept absolutely free from dust. Any dirt is likely to produce a significant increase in the distance from the objective to the plane of the contact surfaces. There is, therefore, a definite risk that the focus will be slightly altered every time the distance piece is removed from the objective. Experience has shown that this risk is not serious with objectives down to ⅔ in. (16 mm.) focal length, or with N.A. values up to 0·30. In such cases the distance piece may be made to give a smooth sliding fit over the outside of the objective, and may be removed and replaced with little fear of disturbing the focus. With objectives of shorter focal length and higher numerical aperture, frequent removal of the distance piece is most inadvisable. In such cases it may be protected against accidental disturbance by moistening the inside surface of the distance piece with a shellac solution before it is finally pressed into position on the objective. A more drastic but most effective method is to cut a thread on the outside of the barrel of the objective mount and on the inside of the distance piece, so that the distance piece can be firmly screwed into position. An objective, permanently fitted with such a distance piece for microphotography without an eyepiece, can still be used for ordinary microscopy. The working distance of the objective, when used with an ocular for visual microscopy, is substantially greater than for microphotography with " tube-lengths " much longer than 6½ in. (160 mm.). The distance piece does not, therefore, prevent the objective from being focused on the specimen.

The working distance of long focal-length objectives (down to ½ in. or 12 mm.) leaves plenty of room for the insertion of a fairly substantial structure between the front of the objective and the emulsion surface. The distance piece can then be made rather after the pattern of the top of a salt-cellar, so that the contact surface is placed very close to the site of image formation (*Figure* 34*a*). The smaller working distance of higher-power and shorter focal-length objectives leaves insufficient space for this type of construction. The distance piece must then take the form of a straight tube with the lower end acting as the contact surface. Most of this surface, apart from three small facets spaced at 120°, should be filed down, so that the final contact surface has a small area less liable to trap dust (*Figure* 34*b*).

Adapting a Microscope for Use with a Distance Piece

The stage of the microscope must be fitted with a rigid sheet of glass or metal to support the emulsion-coated plate when the objective bearing a distance piece is lowered until it touches the emulsion surface. Glass is to be preferred, since it allows a test specimen to be illuminated by transmitted light during the focusing of the distance piece, and should be at least ⅛ in. (3 mm.) thick. The top surface of this supporting glass should, in theory, lie in a plane exactly parallel to the contact surface of the distance piece. Then if the emulsion is coated on glass of which both sides are flat and parallel, the emulsion surface will also lie in a plane parallel to that of the contact surface. In fact, with the " salt-cellar " distance piece, the tolerances are sufficient to prevent the focus from being spoiled by quite an appreciable lack of parallelism (*Figure* 33). Emulsions can be used coated on the glass ordinarily used for photographic plates, and need only be laid flat against the supporting glass fitted to the microscope stage. Film can, for the same reasons, be used quite satisfactorily under these conditions. While the film almost certainly bows slightly inwards when the distance piece is lowered against it, the displacement of focus seems to be too small to affect the image sharpness.

Greater precision is needed with the shorter focal-length objectives both on account of the reduced depth of focus, and because of the impracticability of placing the contact surfaces so close to the site of image formation. The emulsion surface must therefore be allowed to orientate itself until it is lying accurately in the plane of the contact surfaces. This can be done by attaching a ring of sponge rubber to the supporting glass opposite the contact surfaces. The plate is laid with its back against this ring, and when the distance piece is lowered the first contact surface to touch the emulsion forces the plate down, and the plate will therefore rock until all three surfaces are touching the emulsion surface. This arrangement permits great precision to be obtained with glass plates, even when coated on glass of ordinary photographic quality. This is probably because errors, introduced by any lack of flatness over small areas of one side of a plate, are likely to be much smaller than the lack of flatness or of parallelism between the two surfaces observable over a plate as a whole.

A similar system can also be used with emulsions coated on film, provided the film is itself held flat against a rigid support. The author has used supporting microscope slides made permanently " tacky " with a highly-plasticized lacquer such as " Kodaflat ", but this method does not seem readily to give the extreme precision needed. It should, however, be possible to hold film quite flat by placing it against a perforated plate connected to a vacuum pump.

However solidly a distance piece is made, it is unwise to assume that it will not deform slightly under load. Such small deformations are quite harmless if reproducible, and may in practice completely evade detection. The deformation of the apparatus under load will always be the same, if the same pressure is always used to press the emulsion surface against the distance piece. The fine-focusing mechanism of a microscope can be used to obtain reproducible pressure in the following way. In most portable microscopes this mechanism operates by raising the tube against both gravity and the downwards force of a compressed spring. In this type of movement the downwards motion is obtained by allowing the tube to follow the movement produced by the focusing knob. If the fine-focusing knob is turned until the tube is in its lowest position, the tube can be lifted against the force of the spring by raising it with the hand. The tube will be lifted in the same way if the coarse-focusing knob is used to lower the distance piece against the emulsion surface, until the upwards force on the distance piece is sufficient to compress the spring in the fine-focusing mechanism. This spring can be relied on to provide a reproducible pressure, so long as the downwards movement of the coarse-focusing adjustment is stopped immediately compression of the spring is seen to start.

Construction and Focusing of Distance Pieces

Adjusting a distance piece to form a sharp image at a convenient distance is, as Goldberg modestly describes it,(3) " an operation requiring dexterity and patience ". It can, in fact, be a quite formidable task if the image has to be focused at a predetermined distance, since it may finally be necessary to shorten the distance piece a micron (0·00004 in.) at a time. In this instance, above all others, it is more convenient to effect the fine focusing by altering the object distance, so that the distance piece need only be made to focus an image at approximately the required distance.

The focusing operation is carried out by decreasing the length of the distance piece, until the original is sharply focused at a convenient distance. It is thus essentially an operation involving the gradual removal of metal from one end of the distance piece. Appendix II, A shows that this may entail the removal of very small thicknesses, particularly at the end of the operation. Under such circumstances it is only too easy to " overshoot " and completely ruin the work. It is theoretically possible to compensate for such errors by the insertion of shims (very thin sheets of metal) between the end of the distance piece and the bearing surface on the objective, but this method is unsatisfactory for such fine work, since the shims never seem to seat down with the precision required. The reader must therefore use a procedure which makes such accidents least likely. The following method has been found suitable, even for the critical task of focusing a distance piece to be used on a 4-mm. ($\frac{1}{6}$-in.) objective of N.A. 0·65.

The first operation is to determine the approximate length the distance piece should have. To do this, the objective is fitted to the microscope, and is used to project an enlarged image of a single layer of grains (*Figure* 28) on a screen placed in the plane to be occupied by the original. When the enlarged image seen on the screen is sharply focused, the distance from the flange on the objective to the test layer indicates the length the distance piece should have (*Figure* 34). This distance is not easy to measure with great accuracy, and it is therefore better to start by making the distance piece too long.

The main body of the distance piece may now be made from an easily-worked and rustless metal such as brass, and the overall length should be at least 0·01 in. (0·25 mm.) greater than the distance measured in the preliminary test. The internal diameter should be made so that the distance piece either fits smoothly over the objective barrel just in front of the flange, or can be easily screwed on a thread cut on the barrel of the objective. In the former case the back of the tube of the distance piece may be slit with a fine saw, so that the tube can be bent in slightly to give it a " springy " fit over the objective barrel.

The second operation consists of the gradual removal of metal

from one end of the distance piece, until the plane at which the enlarged image of the test layer is focused moves out to the required distance. The rough distance piece should first be fitted on the objective and lowered on the test layer, and the plane of focus ascertained by placing a small magnifier up against the microscope tube and then moving it backwards until an image can be seen. (If no image can be found, it is probably because the distance piece is so long that the enlarged image is right inside the microscope tube, out of reach of the magnifier.) The focusing tables in Appendix II, A are then used to find how much the distance piece should be shortened to bring the image to the required distance. The distance piece is next turned on a lathe to shorten it by perhaps two-thirds of the calculated amount. It is usually more convenient to remove the metal from the end which is eventually to bear on the emulsion. The shortened distance piece should again be tested on the microscope. By alternating the removal of *less* than the required amount, and testing to follow the progressive increase in the distance of the plane of focus, the distance piece should be shortened until it is apparent from the tables that its length exceeds the required figure by not more than 0·001 in. (25 microns). This lathe-work requires constant checking of the length with a micrometer to ensure that too much metal is not removed at any stage.

With very careful use of the lathe, so that only about 0·0001 in. (2·5 microns) is removed at a time, the final adjustment of distance pieces for objectives with focal lengths of $\frac{1}{2}$ in. (12 microns) or more can be done directly on the lathe ; but the adjustment of distance pieces for shorter focal-length lenses should be completed by hand working. Very small amounts of metal can be removed by rubbing the distance piece on a sheet of " Perspex " moistened with a paste of jeweller's rouge. These final adjustments should also be made gradually in several stages, checking the distance of the plane of focus at each stage. At this juncture an ordinary hand micrometer hardly gives the sensitivity needed, and in any case it only offers an indirect indication of the progress of the work. It is, therefore, better to rely entirely on direct checking on the objective for this final stage.

In this way, it is not too difficult to adjust a distance piece so that it focuses at a distance within 10 per cent. of the designed figure. The final precise focusing may then be done photographically with the negative-holder placed at a series of distances along the bench. The intervals should be selected to give appropriate movements of the focal plane with respect to the emulsion surface, and can be readily calculated by multiplying a suitable distance (say, 1 micron) by the square of the degree of reduction given by the objective :

TABLE VI

Approximate Movements of Negative-holder needed to alter Objective-to-image Distance by 1 Micron

Focal length of objective	*Working distance*	*Reduction (approx.)*	R^2	*Movement needed to alter focus by 1 μ*
16 mm.	640 mm.	40	1,600	1·6 mm.
8 mm.	640 mm.	80	6,400	6·4 mm.
4 mm.	640 mm.	160	25,600	25·6 mm.
16 mm.	320 mm.	20	400	0·4 mm.
8 mm.	320 mm.	40	1,600	1·6 mm.
4 mm.	320 mm.	80	6,400	6·4 mm.

This table shows that the longer is the focal length and the less the working distance, the smaller will the focusing intervals need to be.

Merits of Distance Pieces

Distance pieces offer a convenient method for converting any microscope into a fixed-focus precision camera for making microphotographs. They are particularly convenient when a large number of images, possibly from different negatives, have to be made at irregular intervals with a minimum of delay. For this reason they are most useful for such routine operations as the resolution testing of photographic emulsions (Chapter 13). They have proved very satisfactory in resolution cameras constructed in the Kodak Research Laboratories at Harrow (England) and Rochester (U.S.A.),(7) and permit images showing well over 1,000 lines per millimetre to be produced reliably by operators with no previous special skill in microphotography.

It should, however, be recognized that an objective fitted with a distance piece constitutes an inflexible system, which is not to

be recommended when a great variety of work, involving the use of several objectives at different distances, is likely to be undertaken.

Fixed-focus Cameras

Still simpler apparatus can be used if the reader decides only to employ one objective at one distance for making microphotographs. In such cases the distance piece may also constitute the support for the objective. A spring-operated plunger bearing the pressure pad completes the camera.

A simple design for equipment of this type is shown in *Figure* 35.

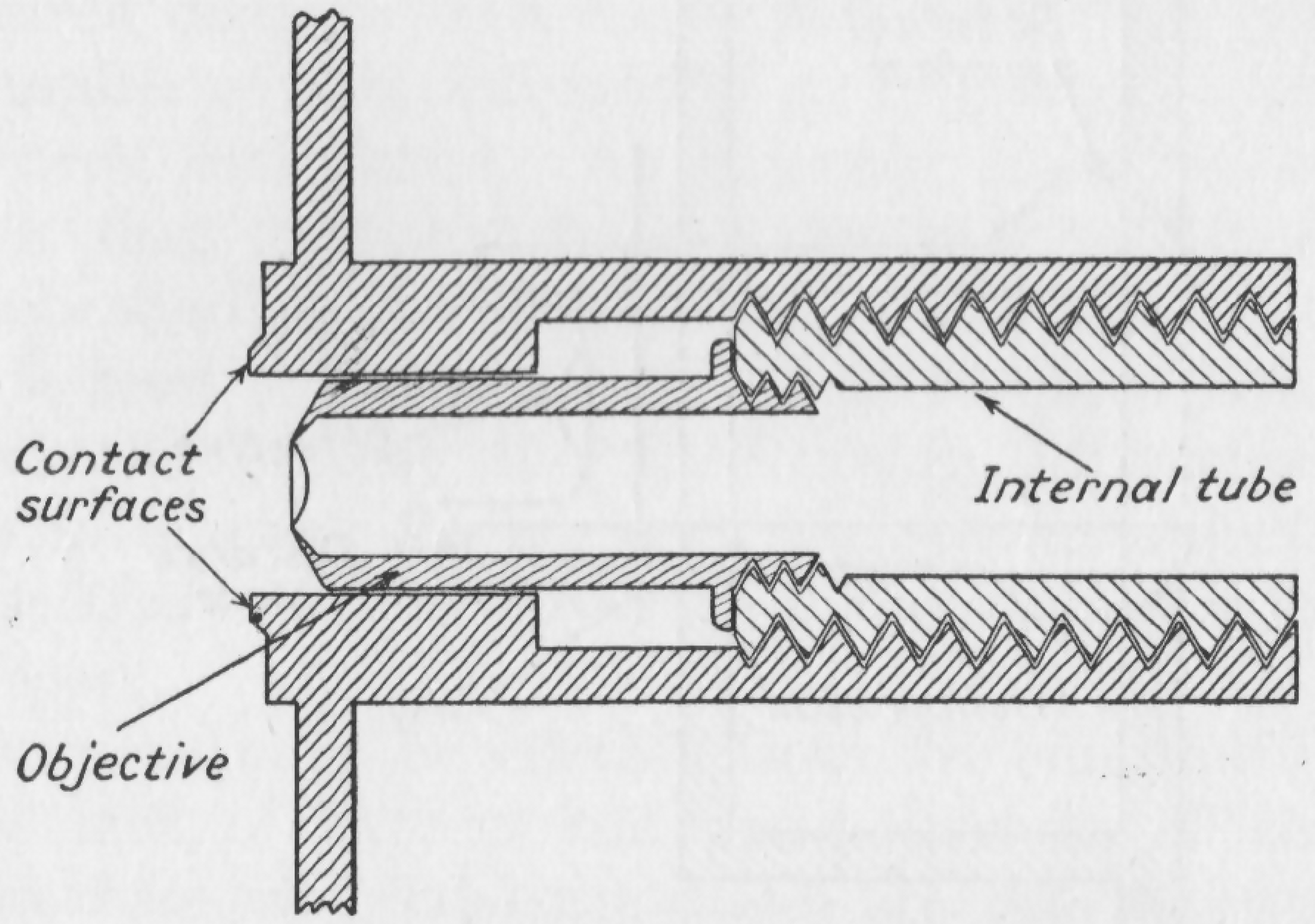


FIG. 35. *Simple Microphotographic Camera.*

An internally-threaded metal tube, shaped at one end to form the contact surfaces, has a smaller tube carrying the objective screwed inside it. Focusing is effected once and for all by rotating the inner tube in its thread, until a sharp image of a focusing-test layer is projected at the required distance. Once the objective has been focused, the inner tube is locked in place with set-screws or with a locking-nut.

The front of the plunger should be made so that the emulsion surface is forced to orientate itself and lie accurately in the plane of the contact surfaces. One method is to use a sponge-rubber pad, but this should not be allowed to rest against the contact surfaces when the apparatus is not in use. Great trouble was at one time experienced by the author as a result of the focus being altered by the contact surfaces becoming contaminated with traces of rubber, but this trouble was cured by attaching a disc of sheet " Bakelite " to the front of the rubber pad. Correct orientation of the emulsion surface was achieved in a different way in a German camera made for copying espionage documents.(8) The pressure was applied by a hinged arm bearing a loose hollow stud, whose back spherical surface fitted into a conical socket. When the hinged arm was allowed to swing against the back of the film, the stud rotated in its socket until perfect orientation of the film against the contact surfaces was achieved (*Figure* 36).

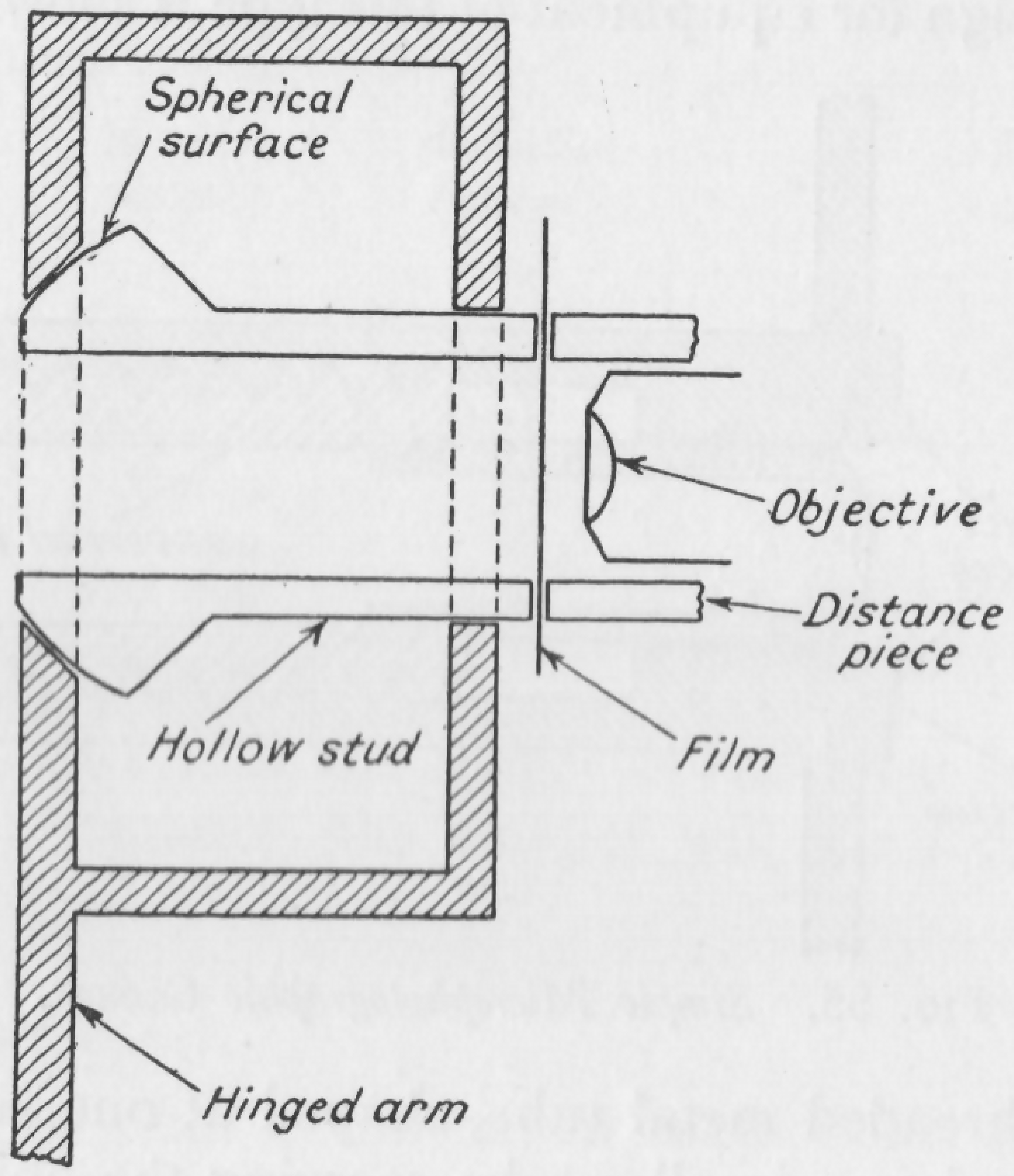


FIG. 36. *Rotatable Stud for holding Film against Distance Piece.*

If equipment, in which focus is secured by a spring forcing the emulsion against contact surfaces, is used to make a series of images on one plate, care must be taken to ensure that the plate is withdrawn from the contact surfaces before moving it laterally for another exposure. Weak springs, for instance, may be fitted to press the emulsion near the edge of the plate, so that the plate falls back as soon as the plunger is withdrawn.

Apparatus of this type is suitable for routine work, either when a few images have to be made at intervals or when large numbers of similar images are required. It can also be fitted with a repeating back, so that many images can be made on a single plate. Care may then be needed to ensure that none of the images is spoiled as a result of abrasion of the emulsion surface during the formation of the other images. With a single row of images this can be avoided by suitable placing of the contact surfaces, but when several rows of images are required, Bovey's technique of focusing by pneumatic gauging could be used (see Chapter 11, page 216).

Variable-focus Apparatus with the Plate registered by the Emulsion Surface

Undoubtedly the most satisfying apparatus to construct and operate is that which allows any suitable objective to be focused at the required distance in a reasonably short time, and yet will enable a number of identical images to be produced once correct focus has been established. An essential requirement of such apparatus is that it should have a focusing mechanism giving distances reproducible to a precision of one micron when the instrument is reset to the same position as before. This condition is adequately fulfilled by the fine-focusing adjustment of most microscopes satisfactory for use with high-power objectives. The rest of this section will show how such a microscope can be adapted for this purpose.

As registration must be effected from the emulsion surface (in view of the lack of flatness and non-uniformity of thickness of photographic base materials) the plates are placed, emulsion-side upwards, against contact surfaces fitted on the under-side of the microscope stage. A stout metal plate, at least $\frac{1}{4}$ in. (6 mm.) thick, should be fitted with contact surfaces around an aperture of sufficient size to allow the objective to focus the image, and should be firmly bolted or clamped to the under-side of the microscope stage (*Figure* 37). Pressure can then be applied to the back of the plate by raising a rubber pad attached to the condenser-holder of the sub-stage. Random variations of focus were at first experienced by the author with this form of apparatus, but these were traced to variations in the bending of the stage when different pressures were applied to the rubber pad. This difficulty was cured by fitting a stop, so that the pad could only be raised to a fixed position, thus applying a reproducible pressure and causing consistent bending (*Figure* 37*a*). Since the same pressure was applied both when focusing and exposing plates, the consistent bending was automatically compensated by a small shift in the focus.

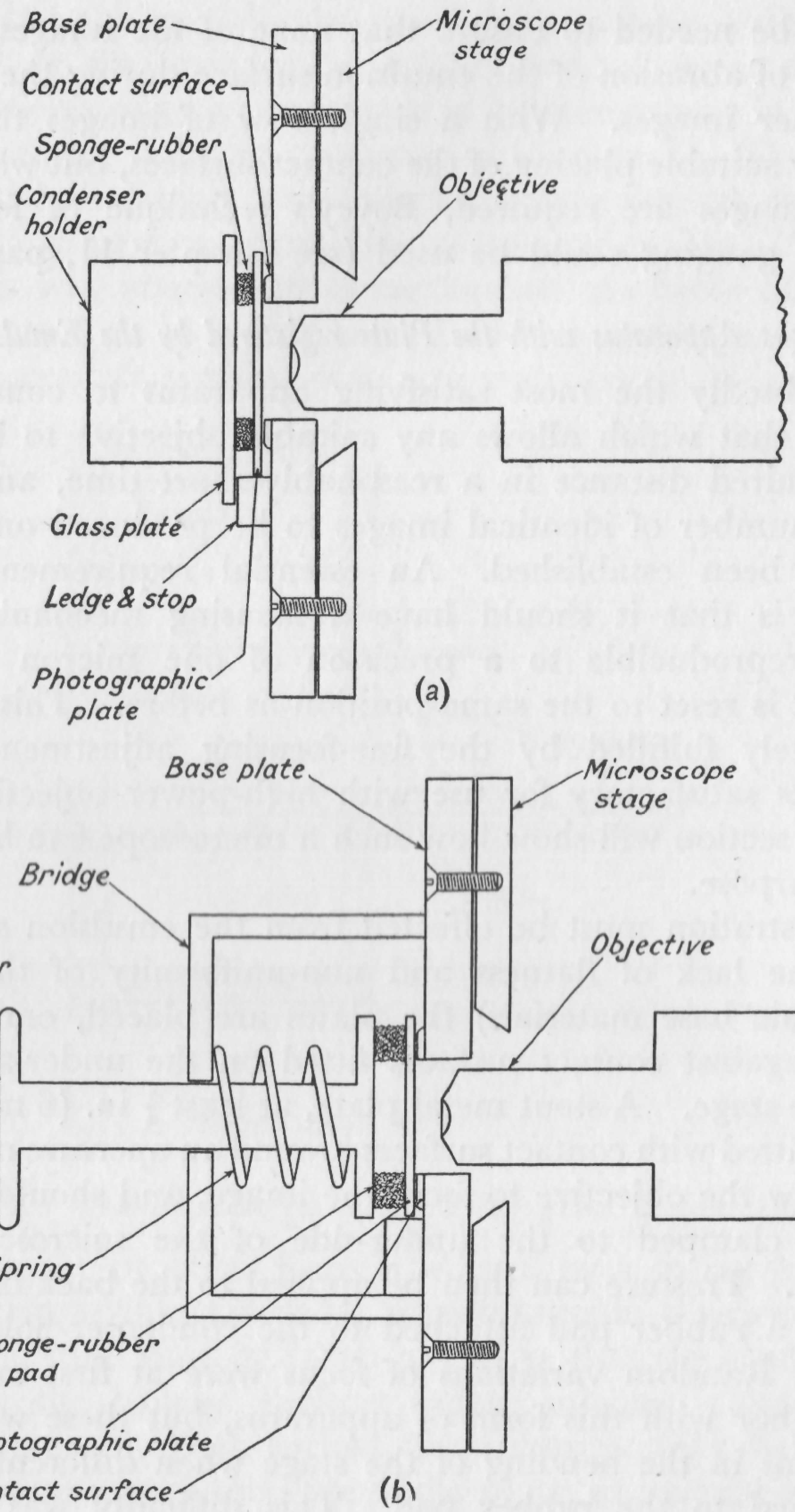


FIG. 37. *Methods for Converting Microscope.*

(*a*) Unit, for attaching beneath microscope stage, whereby pressure is applied with the condenser-holder. Note how ledge supporting plate also serves as stop for limiting movement of pressure pad.

(*b*) More elaborate unit, complete with bridge and plunger bearing pressure pad.

A disadvantage of this method for applying pressure is that the pressure on the stage is applied well away from the point at which the stage is anchored to the microscope, thus increasing the probability that substantial bending will occur. This tendency can be lessened by applying the pressure from a bridge, which is attached not to the stage but to the metal plate fixed underneath the stage (*Figure* 37*b*). The bridge should be attached as close to the point of image formation as the width of the plates to be used permits. Pressure can be applied by a spring-loaded and hollow plunger, through which light may be shone for visual focusing.

If the coarse-focusing movement of the microscope does not permit the tube to be lowered far enough for the objective to be focused on a plate placed at the back of the stage, it may be necessary to fit an extension tube between the objective and the microscope tube.

Focusing of Variable-focus Apparatus

Variable-focus apparatus embodying means for really accurate registration of the emulsion surface can be focused by any of the visual methods described in the earlier sections of this chapter, but the most cunningly devised methods for visual focusing inevitably involve sources of error and uncertainty which can be eliminated by photographic-focusing tests. Now we have already noted that photographic-focusing tests can only be used successfully if the equipment is *designed* and *manipulated* so that the emulsion-to-objective distance can be reproducibly varied by very small increments. The design of the equipment has already been discussed, and we must therefore consider the refinements of manipulation needed to ensure the utmost accuracy.

It is firstly necessary to consider the process of fine focusing with a microscope in some detail. As has already been described, the tubes of most microscopes are forced downwards by a compressed spring. Thus if the fine-focusing knob is turned so that it raises the tube, the movement of the tube will be *against* the force of the spring, and should be very reproducible ; but when the knob is turned the other way the tube only moves as a result of the spring (or gravity) causing it to follow the motion of the fine-focusing mechanism. Any slight " stickiness " in the slides bearing the tube may cause the control when lowering the tube to be less perfect than when raising it.

It is also important to realize that the focusing mechanism tends to be in a greater state of compression when the tube is raised, than when it is lowered. This may cause a small but appreciable difference between the planes of focus obtained by setting the fine-focusing knob to the same position from opposite directions. Such " back-lash " is the source of lack of precision in many mechanisms, including the steering gear of motor-cars. For our present purpose its consequences can be practically eliminated by *always* approaching a desired position by raising the tube away from the stage. If the tube has to be lowered, the fine-focusing mechanism should first be moved to take the plane of focus well below the desired position, so that the final approach is still made by raising the tube. The great accuracy obtainable by this method can be demonstrated by using an oil-immersion objective on a specimen containing very fine detail. Once the focus for a particular layer in the specimen has been found by using the fine-focusing mechanism to raise the tube, it should be possible to re-focus in this layer, without looking down the microscope, by lowering the tube with the fine-focusing knob and then re-setting this knob to the scale position it occupied when the objective was focused visually.

Photographic-focusing tests are conveniently carried out in the following way. The fine-focusing mechanism of the microscope is first adjusted to a half-way position, so that there is plenty of room for both downward and upward movements, and the focus is then found approximately by one of the visual methods. Really critical focus is established by lowering the objective a small distance, and raising it by a number of suitably small increments (Table V), while making an exposure at each position. To obtain the greatest possible sensitivity from this test, allowance must be made for the fact that the density as well as the sharpness of really fine lines alters with changes of focus. The best conditions for exposure and focus can, therefore, only be established with certainty by adjusting *both* the focus and the exposure, until the best *combination* has been found. This necessitates tests in which successive corrections are made separately to the exposure and the focus, and the methods used are described in detail in Chapter 9.

References

(1) Bovey, E., B.I.O.S. report 1552, page 24. (See reference 12, Chapter 3.)
(2) Shadbolt, G., *Phot. J.*, **4**, 79, 1857. (See reference 4, Chapter 5.)
(3) Goldberg, E., *Brit. J. Phot.*, **73**, 462, 1926. (See reference 1, Chapter 3.)
(4) Nicholls, J., *Microscopic Photography : its Art and Mystery.* F. J. Cox (London), 1860.
(5) Martin, L. C. and B. K. Johnson, " Simplified Apparatus for Ultra-violet Microscopy ", *J. Sci. Inst.*, **7**, 1, 1930. (In this paper the authors show how the bending of the stage of a microscope under small loads can be used to give ultra-fine focusing.)
(6) Bovey, E., as reference (1), page 8.
(7) Perrin, F. H. and J. H. Altman, " Resolving-power Cameras in the Kodak Research Laboratories ", *J. Opt. Soc. Am.*, **41**, 265, 1951.
(8) Editors of *Look, The Story of the F.B.I.* E. P. Dutton (New York), 1947.

CHAPTER 7

The Work-room, Camera and Optical Bench

ALTHOUGH EXTREME-RESOLUTION PHOTOGRAPHY subjects most of the materials used to a searching test, the work-room may require less elaborate installation than is wanted for most other photographic processes. The emulsions used for making really minute images have such a low speed that exclusion of all extraneous light is not a serious problem. Some, such as print-out emulsions and the mercury-diazonium material, can safely be operated in rooms lighted by diffuse daylight or by tungsten lamps. Quite bright safelights such as the " Wratten " Series 1 (red), or the Series OB (lime-yellow), may be used with concentrated-Lippmann or wet-collodion materials, which are the fastest emulsions suitable for extreme-resolution work (Chapter 3).

Processing is often simplified by the fact that the area of plate handled may often be so small that it is quite practicable to work in a room without running water. Individual small plates can be processed in from six to eight small tumblers, one each for developing and fixing, and the others for successive changes of wash water. Results of permanent interest can then, if desired, be re-fixed and re-washed later. More elaborate installations are, of course, needed for commercial-scale work such as graticule production (Chapter 11) ; or to cope with the immense numbers of images copied in modern commercial document-copying processes (Chapter 12).

The use of low-speed emulsions also means that stray light from the exposing light source is not so likely to cause accidental fogging of the emulsion. It is therefore not essential to use a " camera ", in the sense of a totally light-excluding box bearing a lens at one end, although the body of an available camera may prove useful. When the apparatus is used in a darkened room, it is generally only necessary to insert the plate and drape a black cloth over the top and around the back and sides of the apparatus, before turning on the exposing light source. A mechanical shutter is not essential, since the light intensity in the image can be adjusted to require an exposure of at least ten seconds, which can be timed with sufficient accuracy by manipulating a lens-cap. More elaborate arrangements can be installed when special requirements demand them. These, however, are more likely to increase the convenience of making a number of images, than to improve their quality. In fact, extreme-resolution photography is one field where the amateur should obtain quite as good results as the commercial worker, since the latter's chief advantage will be in the arrangements made for mass production.

The Optical Bench

A micro-reduction apparatus consists essentially of the illuminating system, the original, the objective and a means for locating the sensitive emulsion. These components must be correctly positioned relative to each other, before making any images. The preparations made to ensure correct positioning influence the convenience of working, and the speed with which the apparatus can be set up. Makeshift arrangements in the long run waste more time than they at first appear to save. It is much better to make some form of optical bench, although this need only be of simple design and rough construction. Its main function is to ensure that the original and the emulsion surface lie in parallel planes normal to the axis of the lens : an ordinary requirement of any photographic copying apparatus. It must also support the camera and original so that vibration causes them to move as one unit rather than to move relative to each other. Further desirable features are that it should :

allow the distance of the original to be varied, while ensuring that its centre always lies on the axis of the lens,
permit the illuminant to be placed at a reproducible distance from the original,
help the illuminant for condenser illumination to be fixed so that its position can be readily adjusted, and firmly held.

Choice between Horizontal and Vertical Benches

The optical bench may be either vertical or horizontal. Vertical apparatus has the advantage that parallelism of the negative and emulsion planes can be readily checked with a spirit level. It must, however, be made with clamps to hold the component parts in position, and is for this reason less easy to construct. Vertical photomicrographic cameras, or vertical enlargers, can be adapted for this purpose. Horizontal apparatus is simpler to construct, and represents the better choice when the whole apparatus has to be built from raw materials. The construction and adjustment of a horizontal bench is described below, and has been used to illustrate some of the principles involved. The dimensions quoted are those used by the author, but may be varied to suit the reader's convenience.

A Horizontal Bench for use with a Microscope

The bench, on which all the other components are supported, is made from a well-seasoned plank 1 in. (25 mm.) thick, 9 in. (22 cm.) wide and 4 ft. (120 cm.) long. This is stiffened with 2 × 1 in. (50 × 25 mm.) battens underneath its entire length (*Figure* 38*a*). A lath having a straight edge bearing a metre scale is attached to one side of the top surface, and is used both to position the components at suitable distances along the bench and also ensure their squareness.

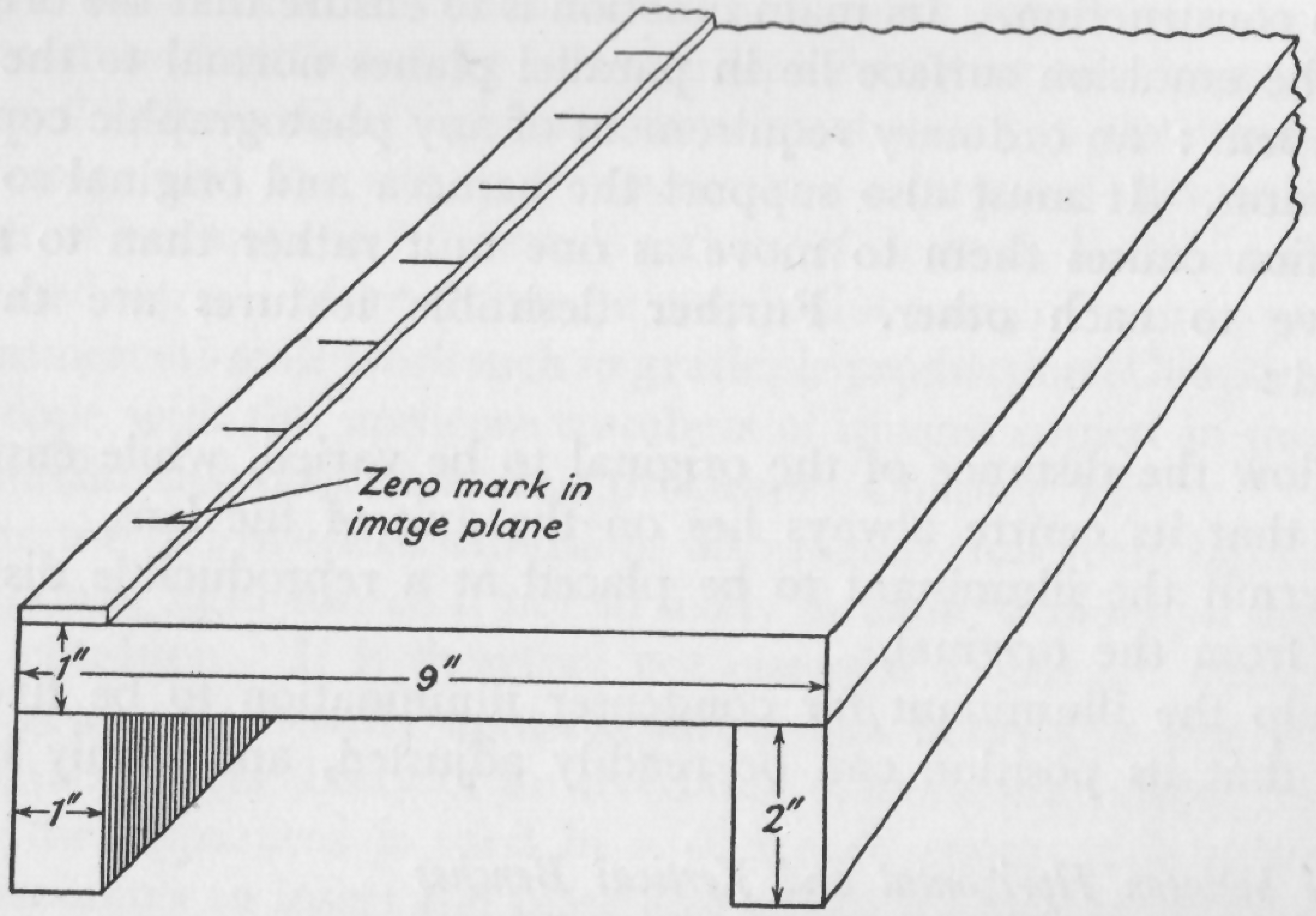


FIG. 38*a*. *Simple Optical Bench.*
Method of construction of bench.

A microscope stand, with its tube in the horizontal position, is placed on one end of the bench, so that the tube points to the other end of the bench and the stage is approximately opposite the start of the scale. Thus the approximate distance of the original ($u + v$, see Chapter 5) can be read off directly by noting its position relative to the scale.

The negative-holder consists of a base-board 12 in. (30 cm.) long, 8 in. (20 cm.) wide and $\frac{1}{2}$ in. (12 mm.) thick, holding an upright firmly and squarely fixed to one end. A 4-in. square hole, with its centre the same height as the axis of the microscope tube, is cut in the upright, and slots to hold the transparency and any light-diffusing screen or filter are fitted around this hole (*Figure* 38*b*). Dome castors are fitted to the under-side of the negative-holder

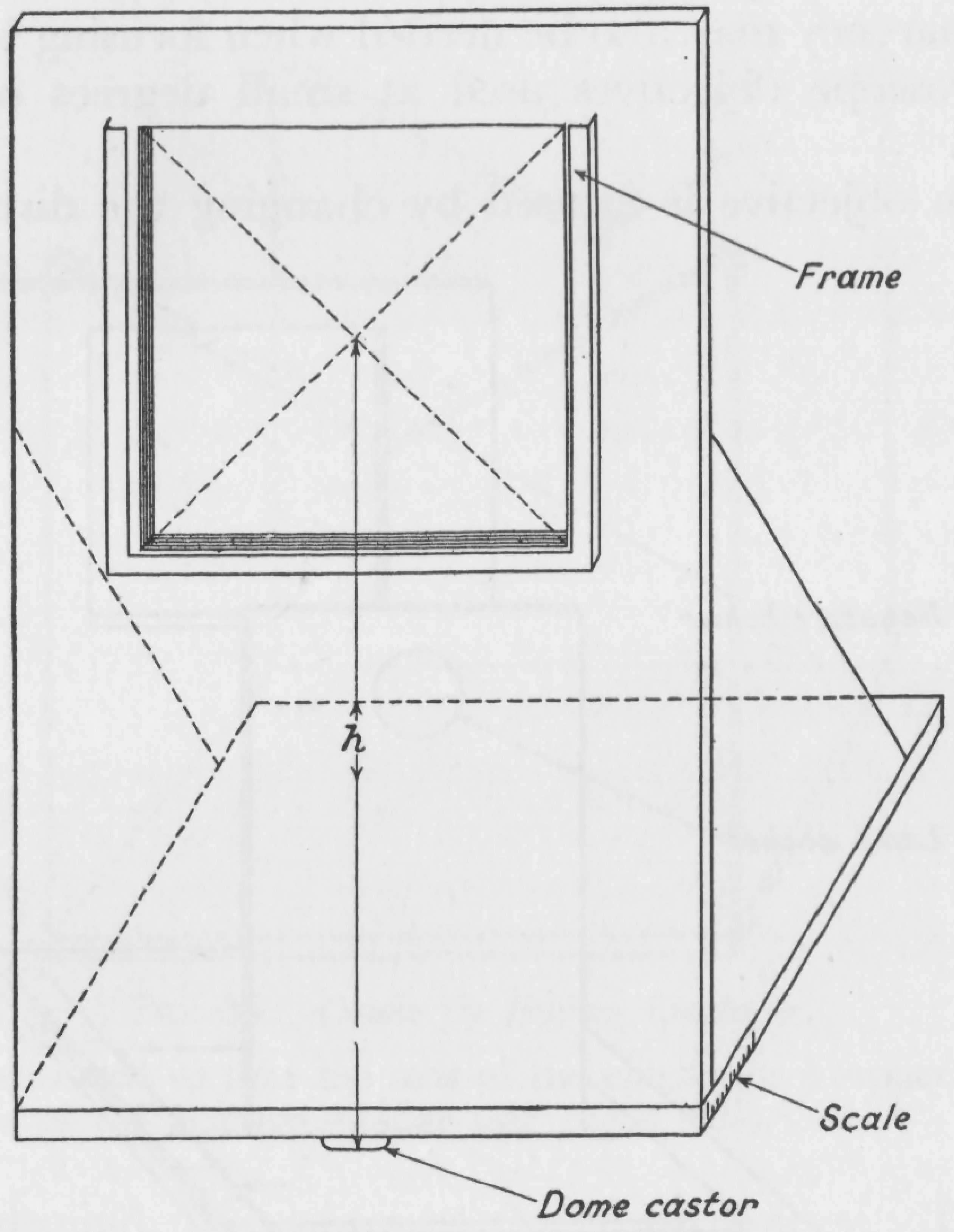


FIG. 38*b*. *Simple Optical Bench.*

Negative-holder : the height *h* equals the height of the axis of the objective.

to allow it to slide smoothly along the bench, and the base-board is marked with an index line to indicate its position relative to the metre scale. Greater sensitivity in positioning can be obtained by using a small scale 9 mm. long and divided into ten parts, instead of the index line. When this small scale, which can be made photographically, is laid against the metre scale it acts as a vernier, allowing small changes in the distance of the transparency to be measured to a tenth of a millimetre. The ability to measure such small movements is valuable when images have to be adjusted exactly to a certain size, even if the total distance from the original to the emulsion is only measured approximately. Small movements of the transparency may also be needed when focusing longer focal-length microscope objectives used at small degrees of reduction (Table VI).

When an objective is focused by changing the distance of the negative-holder from the camera (and particularly if photographic-focusing tests are being made with this method), it is desirable to be able to change the distance with the minimum possible disturbance of the illuminating system. It would, in fact, be convenient to be able to make satisfactory exposures after each movement without having to adjust the illuminating system at all. For this reason, a convenient arrangement is to support the illuminating system entirely on the negative-holder, so that the transparency and its illuminant can be moved as a single unit (*Figure* 38*c*).

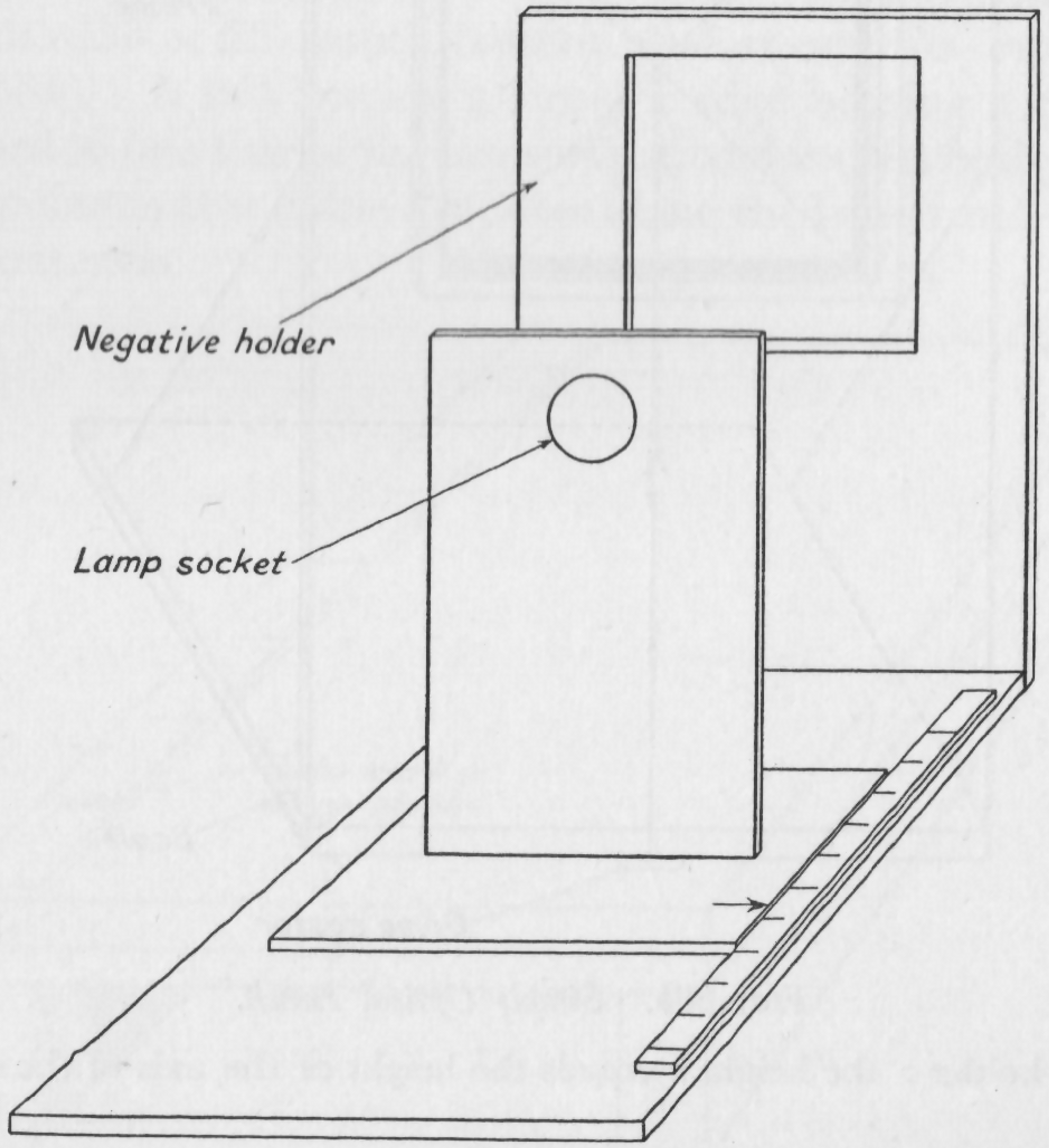


FIG. 38*c*. *Simple Optical Bench.*

Lamp-holder (for use with diffuse illumination) mounted on negative-holder.

If a condenser is used, it may be supported on a V-shaped block (*Figure* 39), so that its axis lies on the axis of the objective and passes through the centre of the transparency. The position of the illuminant has to be adjusted quite critically to the condenser to give uniform illumination (Chapter 8), and it is therefore advisable to construct a lamp-holder with vertical and horizontal slides (*Figure* 40). A laboratory retort stand can be used for the same purpose, but suffers from the disadvantage that the position of the lamp always seems to alter as the clamps are tightened.

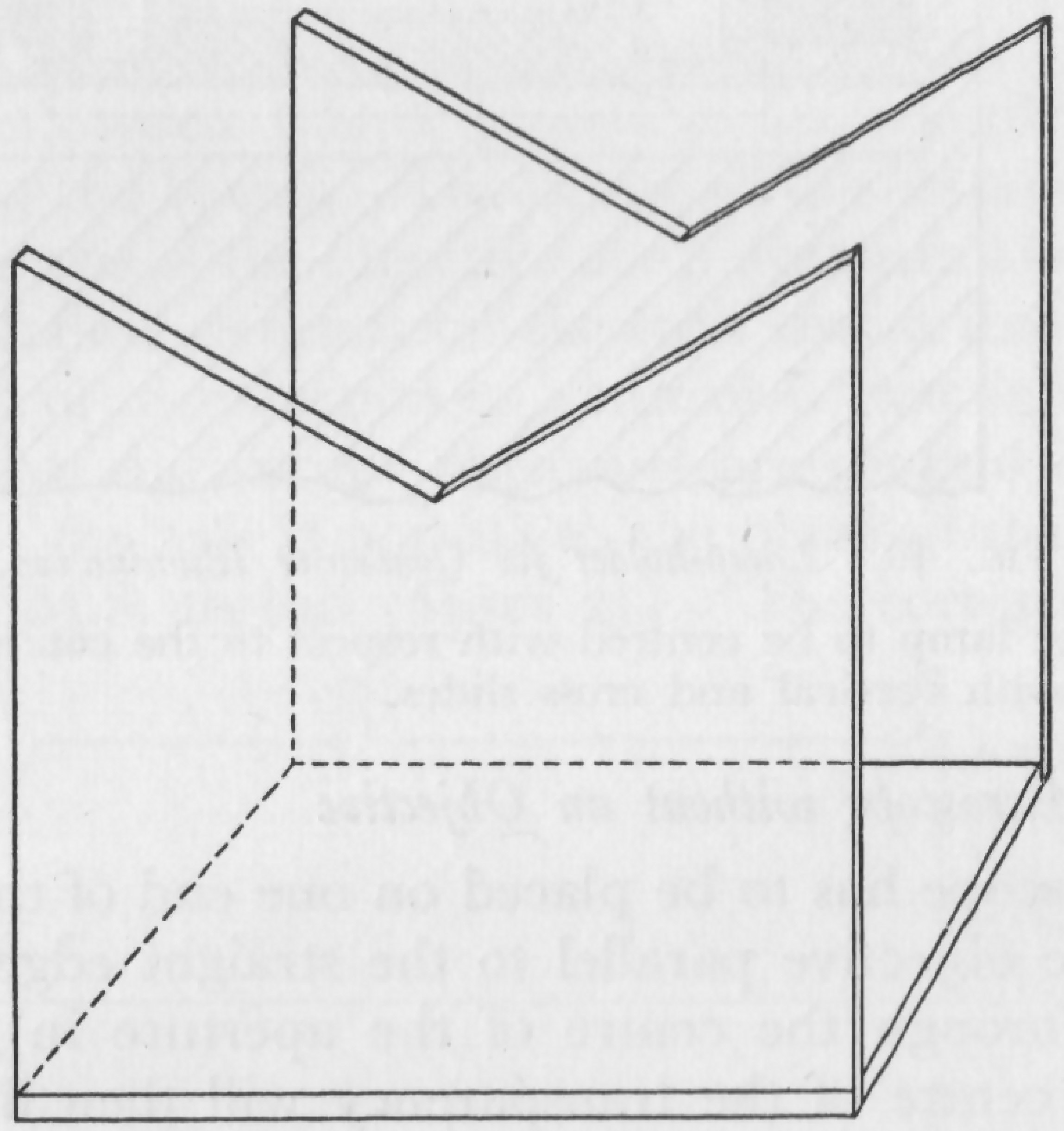


FIG. 39. *Cradle for holding Condenser.*

This is constructed so that the axis of the condenser is opposite the centre of the aperture of the negative-holder (see *Figure* 38*b*).

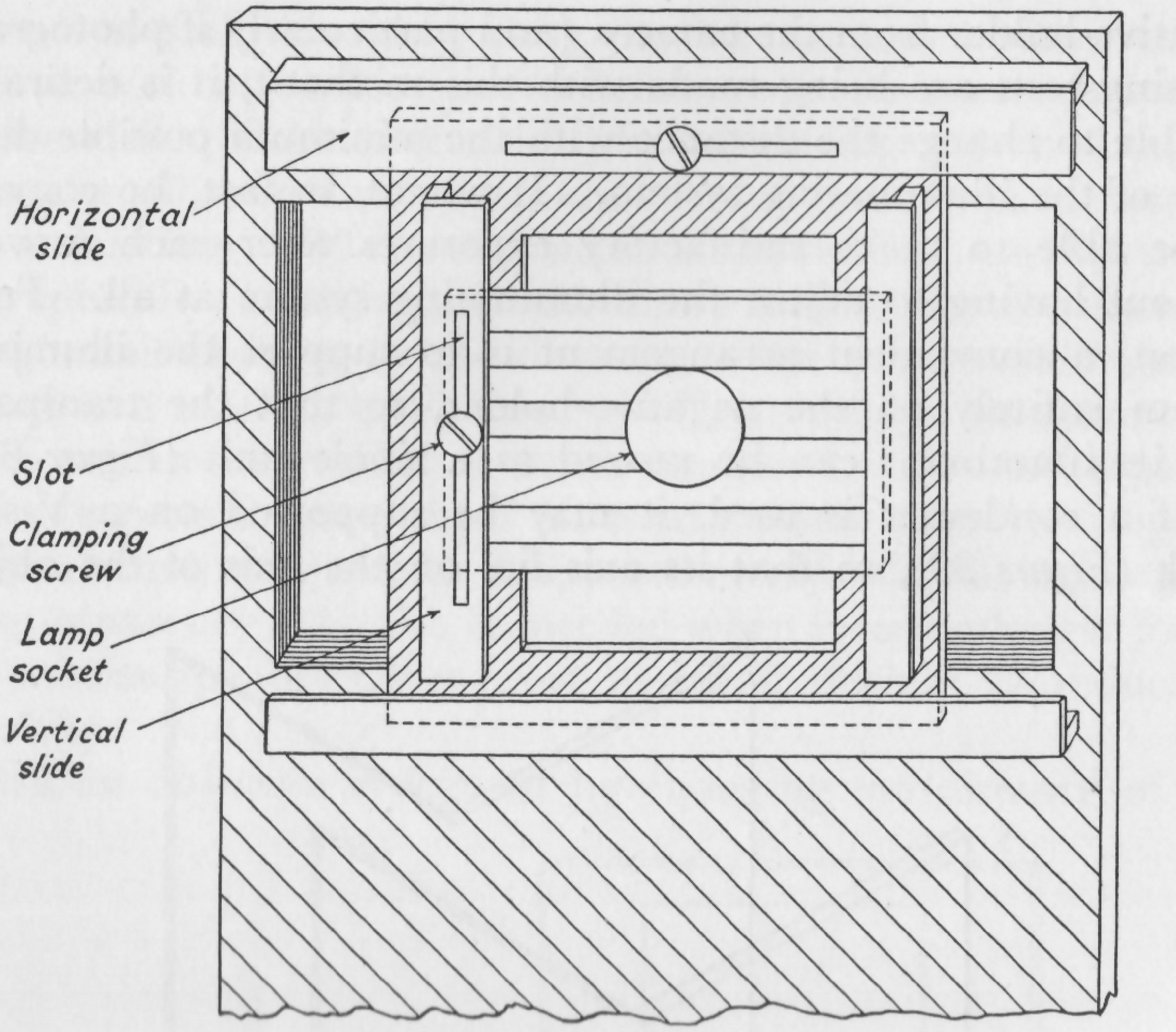


FIG. 40. *Lamp-holder for Condenser Illumination.*

To enable the lamp to be centred with respect to the condenser, the lamp-holder is fitted with vertical and cross slides.

Aligning the Microscope without an Objective

The microscope has to be placed on one end of the bench with the axis of the objective parallel to the straight edge on the lath, and passing through the centre of the aperture in the negative-holder. The centre of the transparency will then lie on the axis of the objective at all distances along the bench.

The first step in making this adjustment is to confirm that the tube of the microscope is truly horizontal. Stand the microscope on a previously levelled surface and use a spirit level to check whether the tube is horizontal. Some microscopes have a small adjustable " stop " screw for making this adjustment. It will, for the moment, be assumed that this inspection is sufficient to ensure that the axis of an objective fitted to the microscope will lie in a horizontal plane parallel to the bench, when the microscope is stood on the bench.

There are several ways of aligning the microscope. Allen (1) describes a method for aligning photomicrographic apparatus which should be equally effective for microphotography. The sub-stage condenser is centred to the objective in accordance with ordinary microscopic practice, and the optical parts of the condenser and the eyepiece and objective are all removed from the microscope. The condenser-diaphragm is then closed down to a pinhole, and a disc of card with a pinhole in its centre is inserted into the eye-piece end of the microscope tube. Now these two pinhole apertures should lie on the axis of any objective used with the microscope, which can therefore be aligned by placing a lamp behind the condenser-diaphragm and observing the position of the spot of light projected through the other pinhole. The microscope is moved until this spot of light shines on the centre of the aperture in the negative-holder, when this is placed at its nearest and furthest distances along the bench. The centre of the transparency should then lie on the axis of the objective at all distances along the bench.

Another method depends on the facts that a line from the eye to the position of its reflection in a mirror is exactly normal to the mirror, and that microscope objectives are centred during manufacture so that the axis is normal to the plane of the flange at the base of the R.M.S. thread (*Figure* 41). The corresponding flange

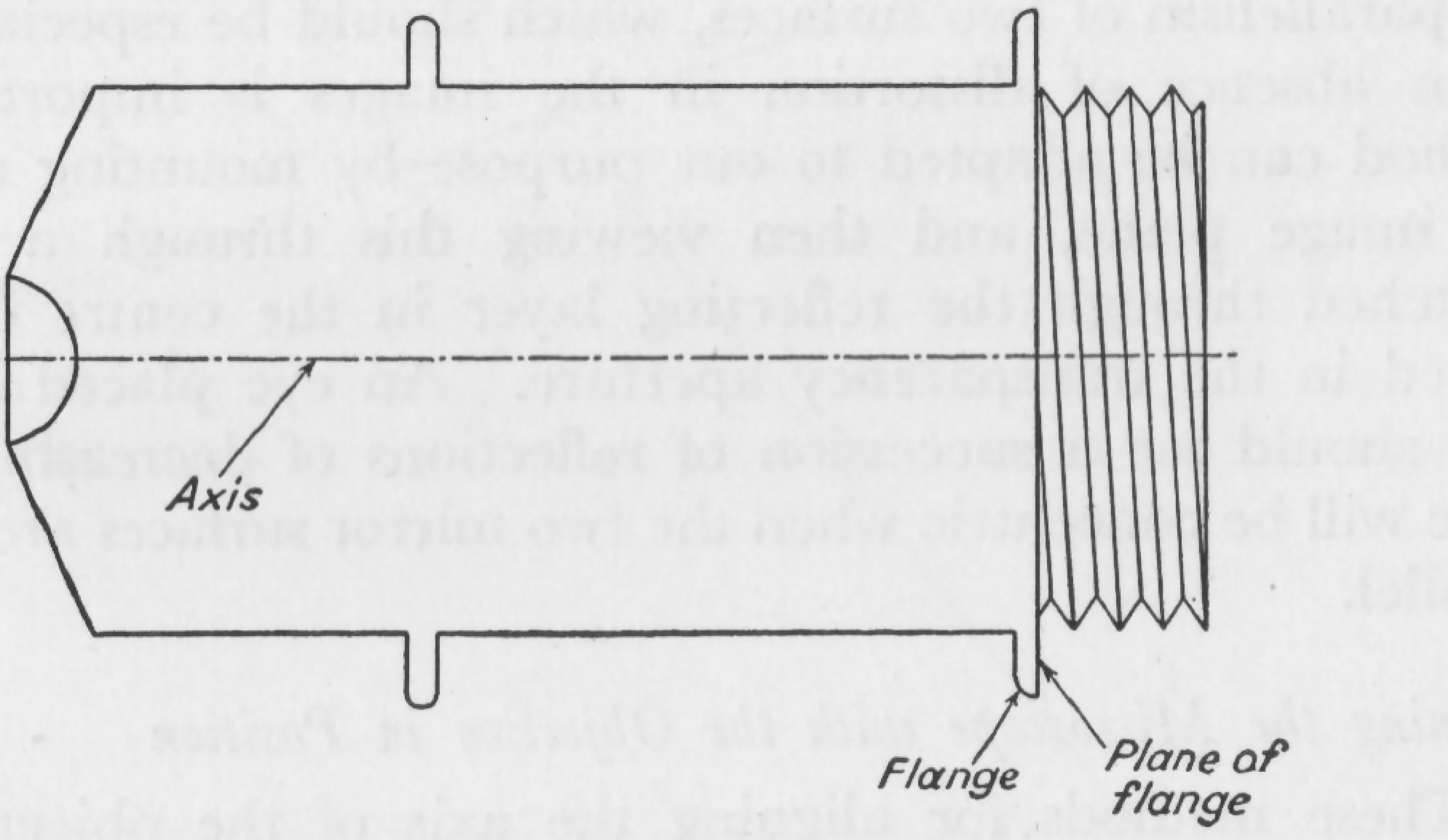


FIG. 41. *Diagram of Microscope Objective.*

In manufacture the lenses of objectives are centred so that their axes are normal to the plane of the flange, and hence to any surface on which the flange is seated.

on the microscope at the base of the tube will, therefore, also be normal to the axis when the objective is screwed right home. The microscope can thus be aligned by holding a piece of mirror flat against this flange, and observing the reflections seen from the negative-holder. A card having a pinhole in the centre surrounded by several concentric circles should be inserted in the negative-holder. The microscope is then moved until the eye placed behind the pinhole sees an image of the pinhole reflected from the centre of the small circle of mirror visible through the microscope tube. This adjustment is simplified by the concentric circles drawn on the card. The alignment should be tested in this way with the negative-holder placed at both its smallest and greatest distances.

This method is sensitive and easy to carry out, and a mirror placed in the emulsion plane can, in the same way, be used to confirm that this too is normal to the axis. In addition, the squareness of the negative-holder can be tested by fitting a mirror in the plane of the original, and viewing this through the microscope tube or condenser diaphragm. This last test also provides a further check on the alignment of the microscope, since the reflection of the condenser diaphragm should be mirrored in the centre of the transparency aperture.

Southey has described another most sensitive method for testing the parallelism of two surfaces, which should be especially suitable when absence of distortion in the images is important.(2) His method can be adapted to our purpose by mounting a mirror in the image plane, and then viewing this through a small hole scratched through the reflecting layer in the centre of a mirror placed in the transparency aperture. An eye placed behind this hole should see a succession of reflections of decreasing size, and these will be concentric when the two mirror surfaces are accurately parallel.

Aligning the Microscope with the Objective in Position

These methods for aligning the axis of the objective are all indirect, since the objective itself is used with none of them. A more direct test is to use the objective to project an enlarged image of a single-grain focusing-test layer on a card placed in the negative-holder (Chapter 5). The projected image usually shows a fairly definite boundary between the axial zone where the grains are sharply imaged, and the outer zones which are unsharp as a result of field curvature. This boundary should be a circle whose centre lies on the axis (*Figure* 28). A more precise way of locating the axis is to examine the apparent movement of individual grains when the magnification is altered. A grain lying right on the axis will not appear to move at all, while those off-axis will appear to move by an amount proportional to their distance from the axis. To carry out the test, focus the image of the test plate on the card when the negative-holder is in a near position, and mark the position of one particular grain close to the centre of the field. Shift the holder to a more distant position, re-focus, and mark the new position of the grain. If it is off-axis, a line passing from the second point through the first should go through the axis. In fact, lines drawn similarly for a number of grains should all intersect at the axis (*Figure* 42).

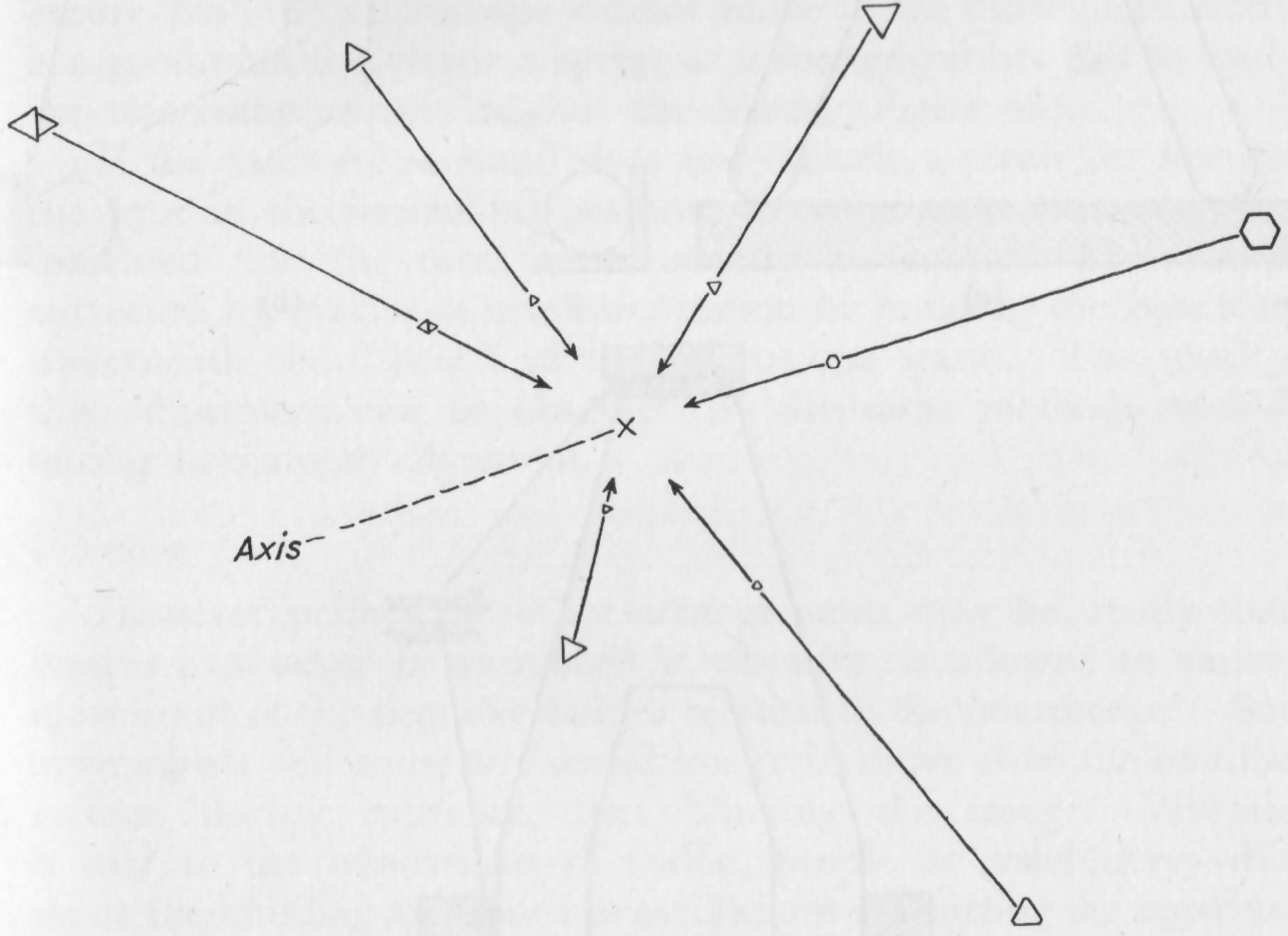


FIG. 42. *Locating the Axis of the Objective.*

Relative positions of several grains when projected at two different magnifications.

Mounting the Microscope

When the microscope has been aligned, locating blocks should be fitted so that it can always be replaced in the same position without losing its alignment. These may be made from a hard wood such as oak or beech, and in their simplest form constitute a straight edge against which the microscope is pushed, and a point to limit its movement when the microscope is slid along in contact with the edge (*Figure* 43). These blocks must of course, be fitted

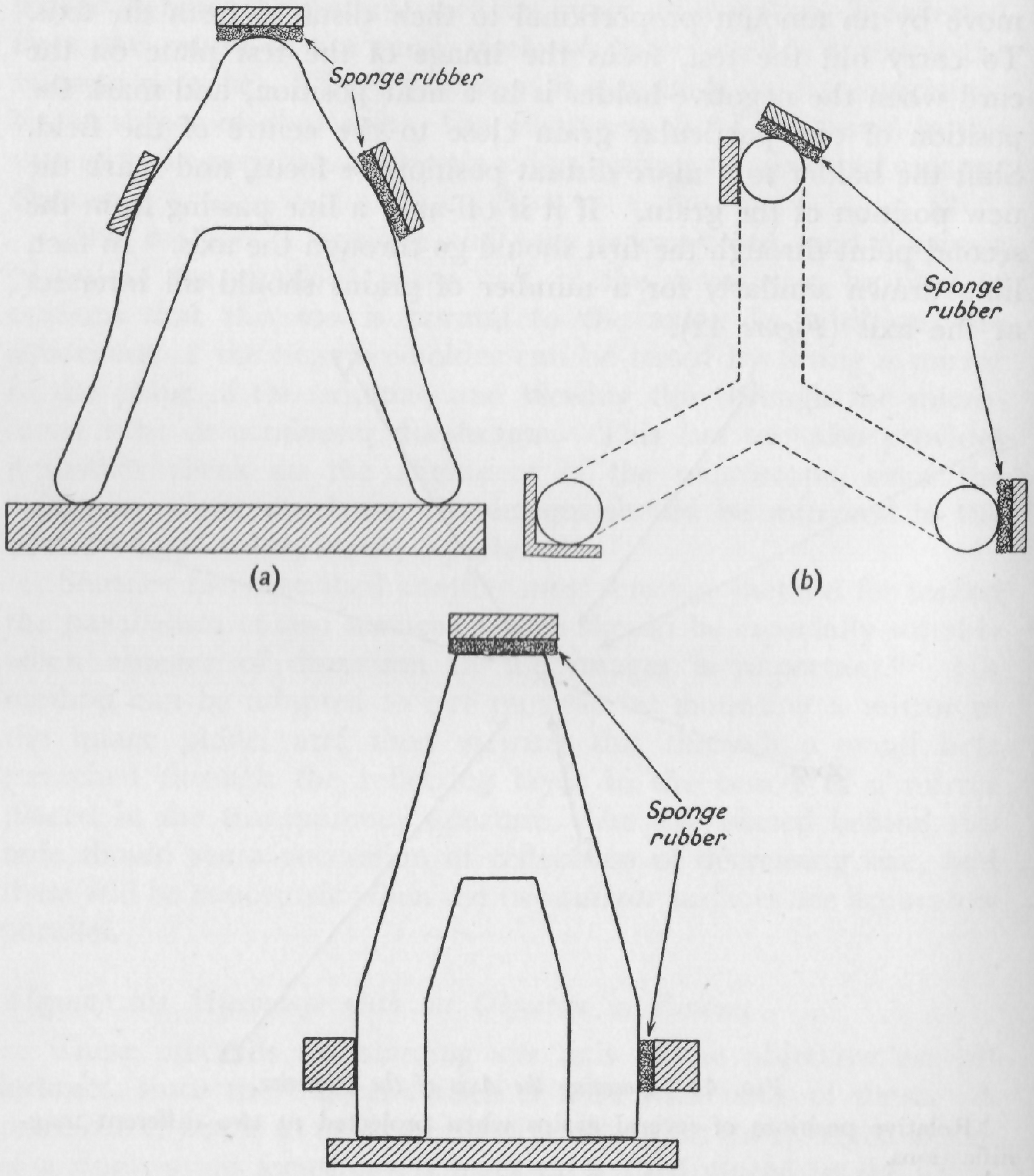


FIG. 43. *Methods for locating Microscopes.*

The positions of the blocks and pressure pads have to be adapted to different designs of microscope foot.

without moving the microscope at all. A good precaution is to fix the microscope temporarily by wedging small pieces of " Plasticine " against the inside of the stand. The blocks may then be stuck in position with liquid glue, and finally screwed down after the glue has dried. Another precise method is to form a plaster cast against part of the base of the microscope stand. Smear a very thin film of oil over the base, and drive some 1½-in. (35-mm.) wood screws about ¾ in. (17 mm.) into the bench at suitable positions around the base of the microscope. The cast can then be built up around the screws and against the base by applying a thick paste of plaster of Paris. After standing overnight it should be possible to ease the microscope away from the cast so that the plaster is neither moved nor broken.

However the locating blocks are constructed, it is difficult to ensure that the microscope cannot move at all during use, and it is a good plan to provide a spring or a sponge-rubber pad to wedge the microscope firmly against the blocks (*Figure* 43).

If the microscope stand does not include a screw for levelling the tube in the horizontal position, the alignment tests may have indicated that the tube is not strictly horizontal. This can be corrected by making a small depression or building the bench up, underneath the " heel " of the microscope stand. The result of this adjustment can be observed by the same methods used for testing horizontal alignment.

Vibration

However perfect the other arrangements may be, really sharp images can never be produced if vibration is allowed to cause a movement of the negative-holder relative to the microscope. Such movements will cause the aerial image to move over the emulsion surface during exposure, thus blurring the image. Vibration is due to the movements of traffic, people or machinery which shake the building and result in oscillations submitting the apparatus to a rapid series of accelerations and decelerations. The oscillations may be slow or rapid, but it is usually the rapid oscillations, whose frequency approximates the natural frequency of vibration of the apparatus itself, that are most likely to produce movements of one part of the apparatus relative to another.

The movement of a point of the image over the emulsion surface resulting from vibration may describe a circle, or an ellipse or a straight line, but the most likely motion is a straight line in either a vertical or horizontal direction. The motion is also likely to resemble that of a pendulum, in that it is most rapid when the point is at its central position, and stops and reverses its direction of movement at the extreme positions. The appearance of an image affected by vibration depends on the total proportion of the exposure time during which the image of a line is projected on each element of the emulsion surface ; and hence on the relation between the width of the line and the amplitude of the vibration. If the amplitude is relatively small, the edges of the total exposed area will receive less light than the centre, thus giving a line with a fuzzy edge on each side. With a large and constant amplitude, a line may be recorded as two lines, corresponding to the extreme positions receiving the greatest exposure as a result of the slow movement of the image at the ends of its swing, and the space between will have a lower density. Vibration can also result in the complete disappearance of fine lines, if the area over which the light is spread is so large that no density can be produced. Another feature of images spoilt by vibration is that their appearance depends greatly on the angle between a line and the direction of swing, since no deterioration of the sharpness of a line will result when the direction of vibration is parallel to the line (*Figure* 44). The resulting apparent astigmatism will be uniform over the whole area of the field, as contrasted with astigmatism of an objective which tends to become worse in marginal zones (Chapter 5).

If unsharp images are produced as a result of vibration, the cause of the trouble may be obvious from the symptoms described above, but vibration should always be suspected if images of very variable quality are being produced in the absence of any obvious defect in the mechanism for maintaining focus.

The problem of eliminating the effects of vibration is precisely the same as in photomicrography. The various parts of the equipment must all be mounted so that they have no tendency to rock or wobble, but move with the bench as a single unit. The bench should be so stiff that any vibrations allowed to reach it cannot result in appreciable torsional vibration of the bench itself. These elementary precautions will already do much to lessen the harmful effects of vibration. It is also usually advantageous to weight the

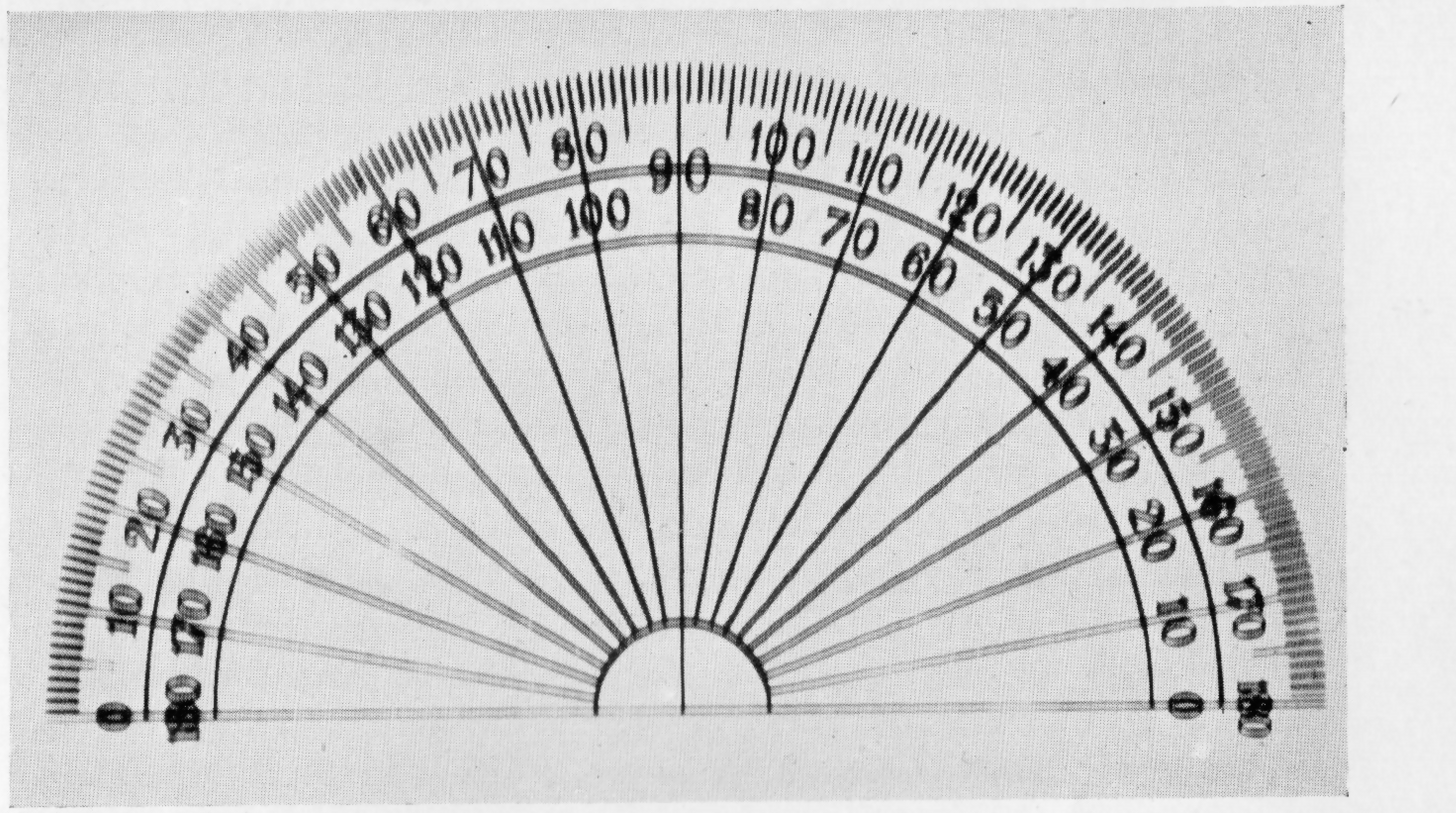


FIG. 44. *Influence of Vibration on Photographic Image.*

No loss of sharpness occurs along the 90° radius parallel to the vibration, and maximum unsharpness is produced at right angles to this direction. Note how the simple harmonic motion has tended to split the image into two lines, and coincidence of intensity maxima produces spurious sharpness of the scale at 0° on the left.

[*Facing p. 142.*

bench with bricks or other heavy weights, so that a large force is needed to produce a given acceleration, and mount the bench on resilient supports which will only transmit vibrations very sluggishly. Under these conditions only the low frequency " soft " components of vibration are likely to be transmitted to the bench, and it is improbable that these will cause blurring of the image.

Sponge-rubber is an excellent material for combating vibration, and may be used to support both the bench and the table on which it is laid. For photomicrography Allen suggested placing pieces of 1-in. thick sponge-rubber under the legs of the table, with a metal plate between the leg and the rubber to distribute the load over the entire area of the pads.(3) The area of the rubber should be sufficient to allow the table to sway gently when pushed hard. This method cannot be used when working on built-in laboratory benches, and the optical bench itself must be resiliently mounted. Sponge-rubber pads fixed at intervals along the stiffening battens of the bench proved a satisfactory precaution against vibration, even when working next to a busy passage in a building which was also vibrating from machinery.

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(1) Allen, R. M., *Photomicrography*. D. Van Nostrand (New York), 1943, page 112.

(2) Southey, R., " Squaring the Camera to the Copy ", *Brit. J. Phot.*, **97**, 585, 1950.

(3) Allen, R. M., as reference (1), page 106.

CHAPTER 8

The Original and its Illumination

THE SUCCESSFUL PRODUCTION of microphotographs depends on many factors, some of which at first appear to merit but little thought. The choice of the " original " for the final stage of reduction, for instance, can exert a profound influence on the subsequent task. The present chapter deals with the factors to be considered when choosing an original, and the methods used to illuminate it.

The Form of the Original

The original used for the final reduction may be multi-coloured or in monochrome, and may consist of solid objects or opaque pictures, or of a transparency or intermediate negative. As no photographic process yet appears to have been worked out for making truly microscopic coloured photographs * (Chapter 3), there seems little point in using a coloured original. In view of the low photographic speed of extreme-resolution emulsions, transparent originals are generally to be preferred, since they facilitate the production of a really bright image at the emulsion surface and hence avoid the necessity for inconveniently long exposures. In fact, only the fastest extreme-resolution emulsions (concentrated-Lippmann or wet-collodion) are suitable for photographing opaque originals by reflected light, and these emulsions will usually give tolerably well-exposed images of objects illuminated by direct sunlight with an exposure of less than one minute at F/2. A distant scene photographed with a 2-in. (50-mm.) microscope objective on a concentrated-Lippmann emulsion is shown in *Figure* 45. Comparison of this enlargement with photographs to the same scale, made with an ordinary camera at shorter distances, shows that the

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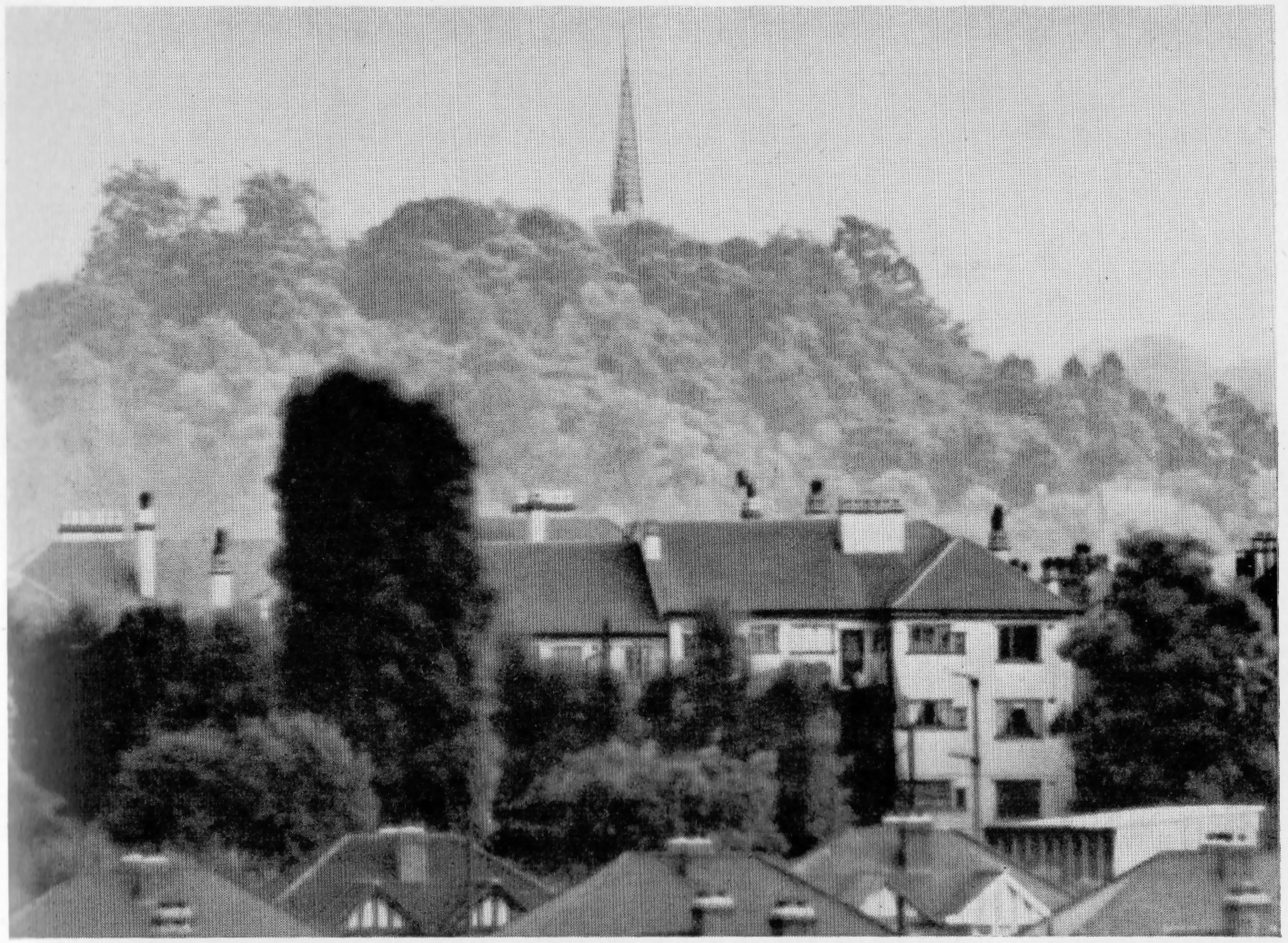
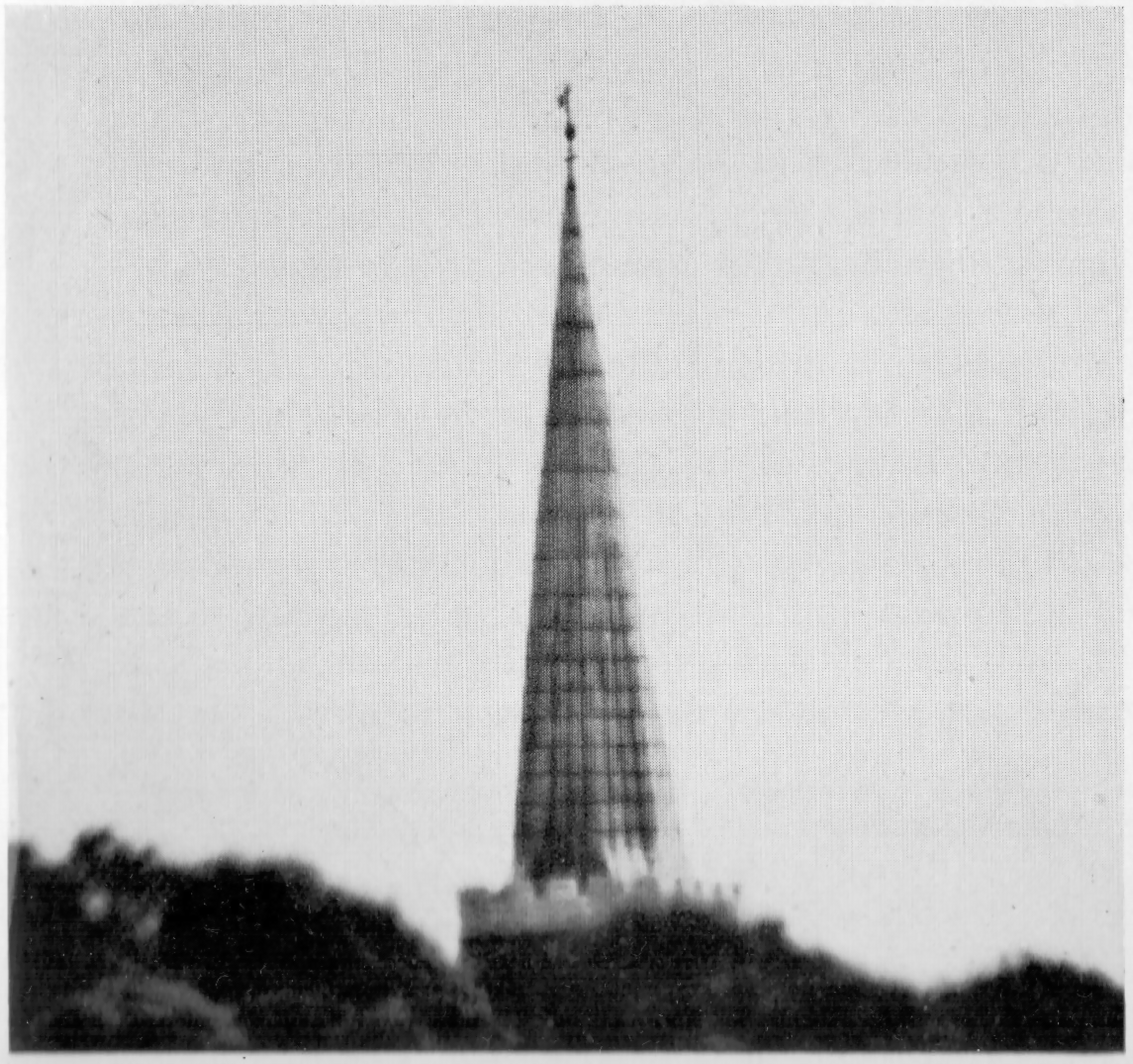
* Microscopic coloured " paintings " have, however, been made by the assembly of the brilliantly-coloured scales from butterflies' wings.(1)



(*a*) Photomicrograph (× 36) of image on Maximum Resolution plate, made with 2-inch Watson " Holos " objective.



(*b*) Further enlargement (× 130) of spire, which was $1\frac{1}{2}$ miles away.

FIG. 45. " *Telephotographs* " *made with Microscope Objectives.*

microphotograph possesses the foreshortening so characteristic of telephotographs.

The Characteristics of Transparencies

For convenience, transparencies should neither be too small nor too large : images having heights between 1 in. (25 mm.) and 4 in. (100 mm.) have been found to offer a suitable compromise. If much smaller transparencies are used it becomes less easy to produce images with the perfection needed to avoid difficulties in the final reduction, while large transparencies are more difficult to illuminate with the required brilliance and uniformity.

Very large transparencies have, however, been used by French manufacturers for the mass-production of microphotographs. Their equipment employed a battery of objectives to project a large number of similar images side by side on a single plate (*Figure* 46*a*). It

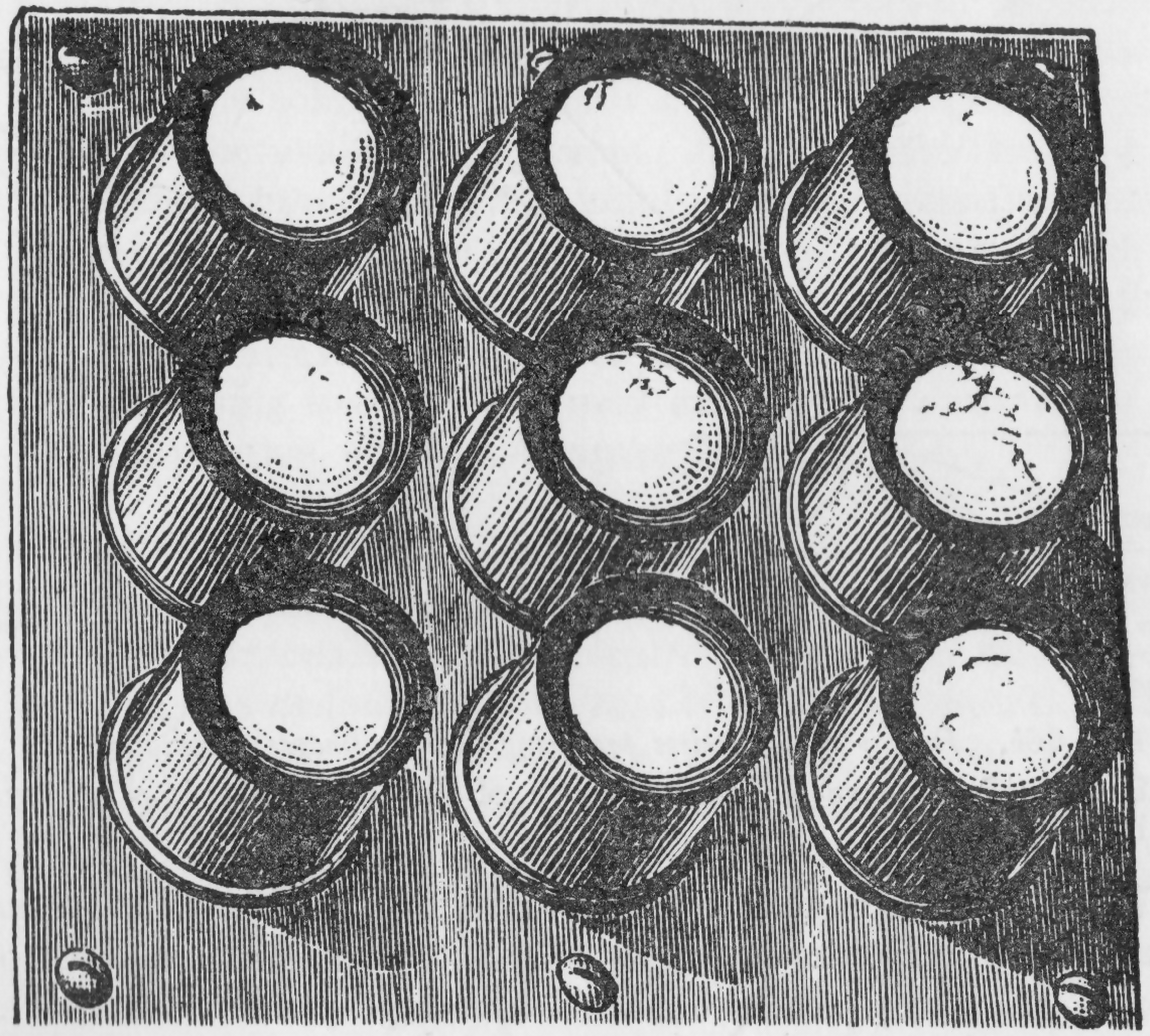


FIG. 46*a*. *Battery of Objectives producing Several Images simultaneously.*

Battery of objectives mounted on lens board.

Reproduced from Fabre's " Traité Encyclopédique de Photographie " (Paris, 1890) 4, p. 76.

has been stated that as many as 50 objectives were used together in this way.(2) The number of images which can simultaneously be produced by this method is limited by the field covered by the objectives, since those images formed by the outermost objectives must lie well off the axis. This difficulty was combated by using a large negative, so that an exceptionally long working distance was required to give the necessary degree of reduction, and the images formed by the outermost objectives lay relatively closer to the axis (*Figure* 46*b*).

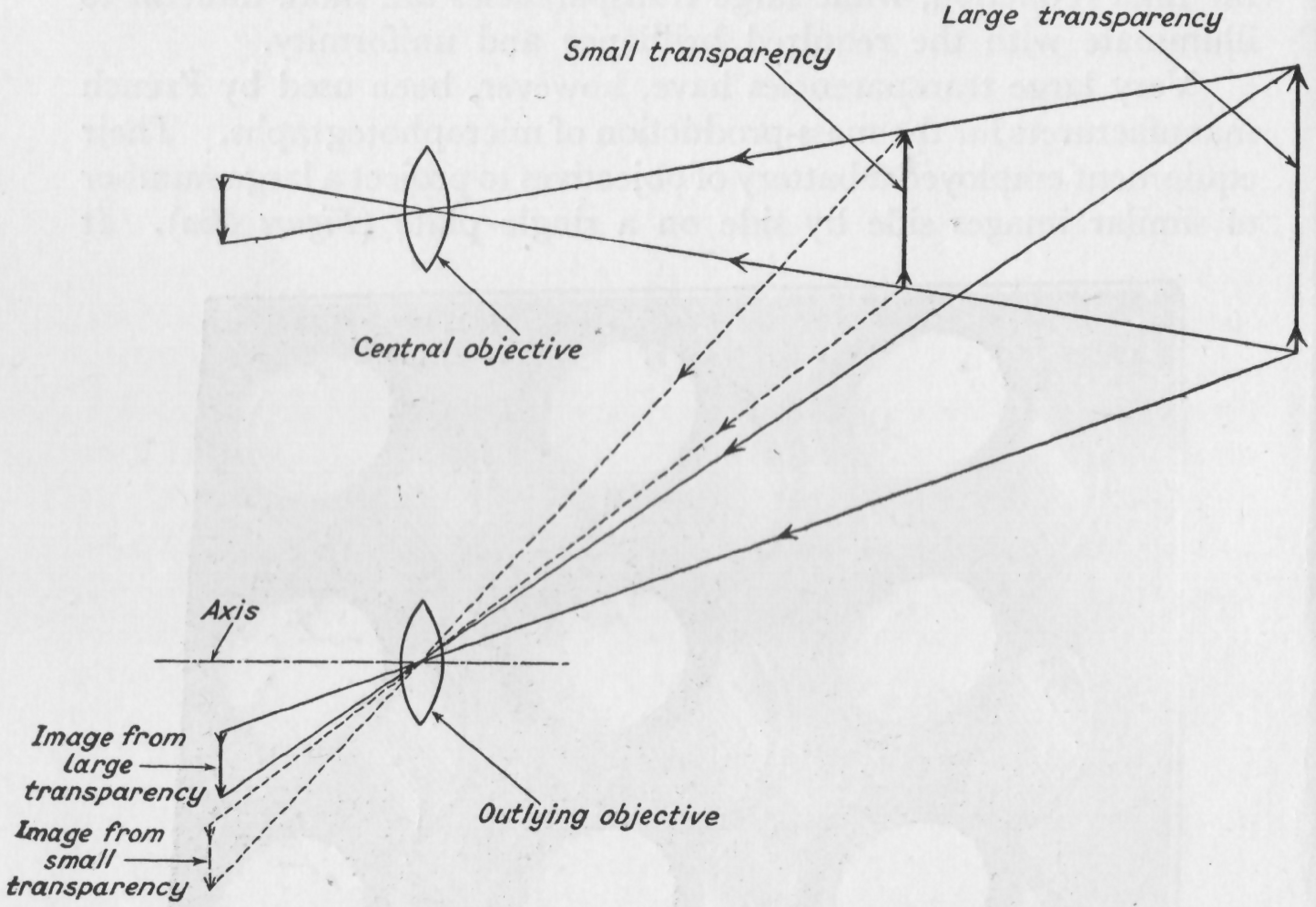


FIG. 46*b*. *Battery of Objectives producing Several Images simultaneously.*

Influence of negative size on distance of images from axis of outermost objectives.

The type of image chosen for reproduction and its photographic " quality " both influence the subsequent reduction to microscopic dimensions. The production of microphotographs is a task in which the greatest obstacles occur in the final stage, and it is thus only reasonable to start with an original well-suited to the microphotographic process used. Three main matters have to be considered :

(*a*) whether the original image should be a " negative " or a " positive ",

(*b*) the contrast should be adjusted to suit both the subject-matter and the characteristics of the extreme-resolution emulsion,

(*c*) the fine detail in the original should comply with the requirements discussed below.

" *Negative* " *or* " *Positive* " *Originals*

In Chapters 3 and 4 we noted that extreme-resolution emulsions can be made to give tones which get darker in the same order as those of the original (direct-" positive " reproduction) or are tonally reversed (" negative " reproduction). In the first case the order of the tones in the transparency must clearly be that required in the final image, and the reverse of the tones of the final image must be shown by the transparency in the second case. Now a common (but unsophisticated) practice is to select the tonal direction of the transparency solely on the basis of the reproduction most readily given by the available emulsion. In fact, better results can often be obtained by choosing the emulsion and transparency *together* to suit the final image required (Chapter 9). Factors which have to be considered are lens flare (Chapter 5), the adverse influence of some types of reversal process on image sharpness (Chapter 4), and any overriding needs which may indicate the desirability of using a direct-positive process (Chapter 11, page 216).

The Contrast or Density Range of the Original

The contrast of the original transparency should be adjusted to suit the characteristics of the extreme-resolution emulsion, in the same way as ordinary photographic negatives should be made to suit the properties of the medium on which they are to be printed. We must, however, first decide whether the subject-matter is to be a " continuous-tone " or " line " picture.

Photographs of solid objects usually show a continuous range of tones between the extremes of light and shade present in the picture, and uniform light or dark areas in the original are depicted as patches of even density. They are more difficult to reproduce on a really small scale, since the granular structure of a continuous-tone image is more readily seen than that of a line image composed of developed grains of the same size (Chapter 3). Thus for the same emulsion, lesser degrees of reduction are permissible for continuous-tone than for line images.

It is generally inconvenient, and sometimes impossible, to alter the contrast of microphotographic emulsions by changing the processing conditions ; and it is better to adjust the density range of continuous-tone transparencies to suit the emulsion used for making the final images. Some extreme-resolution emulsions, such as the commercial concentrated-Lippmann materials, were designed for line work, and their high contrast means that negatives of low contrast must be used to ensure reasonable tone reproduction (Chapter 4). Others, such as Goldberg's collodion print-out emulsion, have a moderate contrast suitable for reproducing " snapshot " negatives ; together with a grain structure so fine that really minute images are practicable.(3) Wet-collodion can also be made to give a similar convenient level of contrast, but examples of work with this material seen by the author all indicate that the grain tends to become obtrusive with image heights less than $\frac{1}{25}$ in. (1 mm.). If it is desired to produce a microscopic image from any available negative, the mercury-diazonium process is probably the most suitable, since the emulsion contrast can be varied by changing the humidity and exposure intensity (Chapter 3).

With line images, the density range of the transparency must at least be sufficient to ensure that the lines will be recorded with an adequate density by an exposure which just fails to print through the background. A high-contrast negative must therefore be used with the softer-working emulsions such as wet-collodion or collodion print-out. The high contrast, and consequent small exposure latitude of concentrated-Lippmann emulsions, necessitates a transparency of a special type, in which all the lines have the same density. Now the visual appearance of high-contrast line negatives is very deceptive, since the great contrast between the background and the lines can conceal the fact that the density of the lines varies from point to point. The most certain way to ensure uniform density in the lines is to make them absolutely transparent, so that the density is, in fact, zero. The transparency should be made by copying an indian-ink drawing on a high-contrast " process " material (such as " Kodak " B.4 or " Ilford " Thin-Film Half-Tone plates), which should be developed in a caustic-hydroquinone solution (Appendix I, A). These plates should be exposed so that they give a background density not greater than 1 or 1·5 on full development, and this should be quite adequate for use with the concentrated-Lippmann emulsions, while giving very clear lines. A useful test to apply to such line negatives is to view them when dry through the back, while pressing the emulsion surface firmly against a white card. Since the light reflected from the card has to pass through the emulsion twice before entering the eye, the effect of any density in the lines is doubled, and differences are correspondingly easier to see. Transparencies which do not satisfy this test may still be made usable by " cutting " and intensifying (Appendix I, D).

The Fine Detail of the Original

Just as line images are simpler to reproduce than continuous-tone pictures, so certain types of line image are easier to reproduce than others. Images showing great variations in the proportions of black to white in different areas, for instance, are difficult to reproduce. As we shall see later (Chapter 9), large exposed areas require substantially less exposure than smaller areas, and this combined with the limited exposure latitude of high-contrast emulsions can hinder the making of a satisfactory image. It also often happens that the density of one part of an image may be increased by scattered light or flare coming from immediately adjacent areas of the image. This tendency leads to " clogging " of the detail where several lines run together, or to variations in the average blackness of words in a page of print, so that long words or words with the letters placed closer together may reproduce darker than their neighbours. Difficulties of this type can be counteracted by masking the transparency to equalize the printing values of different parts of the image. It may, in some cases, be sufficient to place a neutral density behind the heavy lines ; while an " unsharp " mask may be needed for such difficult tasks as equalizing the printing values over a transparency depicting a page of print.(4)

Finishing the Original

All retouching of the picture must, of course, be made on the transparency, but it is not generally necessary to " spot " as thoroughly as with negatives intended for either contact printing or enlarging. This is because "pinholes" in the transparency tend to be smaller than the lines of the image, and would need an exceedingly long exposure to make them appear in the microphotograph. Only the more obvious blemishes need therefore be painted over with an opaque medium. The reader is more likely to be troubled by small refracting or light-scattering particles in the background in cases when the transparency has black lines on a clear background. These are most troublesome with condenser illumination, since they divert the light in their neighbourhood, and will tend to be recorded as transparent spots in the reduced image. Their effect can be greatly lessened by using Canada Balsam to cement a cover-glass on the surface of the transparency. This is in any case an excellent practice, since it protects valuable transparencies against dust and damage. When a transparency with a cover-glass is illuminated with a condenser system, it may sometimes be possible to see a "ghost" image to one side of the main lines of the image. This is produced by internal reflections in the glass, but its intensity is much lower than the main image, and it is most unlikely to show in the reduced image.

Illumination for Microphotography

Whatever method of illumination is used, it should provide a high and very uniform light intensity over the entire area of the transparency or original. The principles employed are the same as in photomicrography or photographic enlarging, but the details of their application are different. One special difficulty is that the reduced aerial image given by the objective is too small to permit convenient visual examination of the uniformity of illumination in the focal plane. This has therefore to be judged by microscopic inspection of actual photographic images. The unusual dimensions of the apparatus introduce subsidiary problems. In enlargers, for instance, the distance from the objective to the condenser is usually less than twice the distance from the condenser to the illuminant. In microphotography the objective-to-condenser distance may be ten or more times the condenser-to-illuminant distance, so that the objective subtends a much smaller angle at the condenser (*Figure* 47), causing optical problems which are discussed below.

In the remainder of this chapter we shall discuss the following three types of illuminating system :

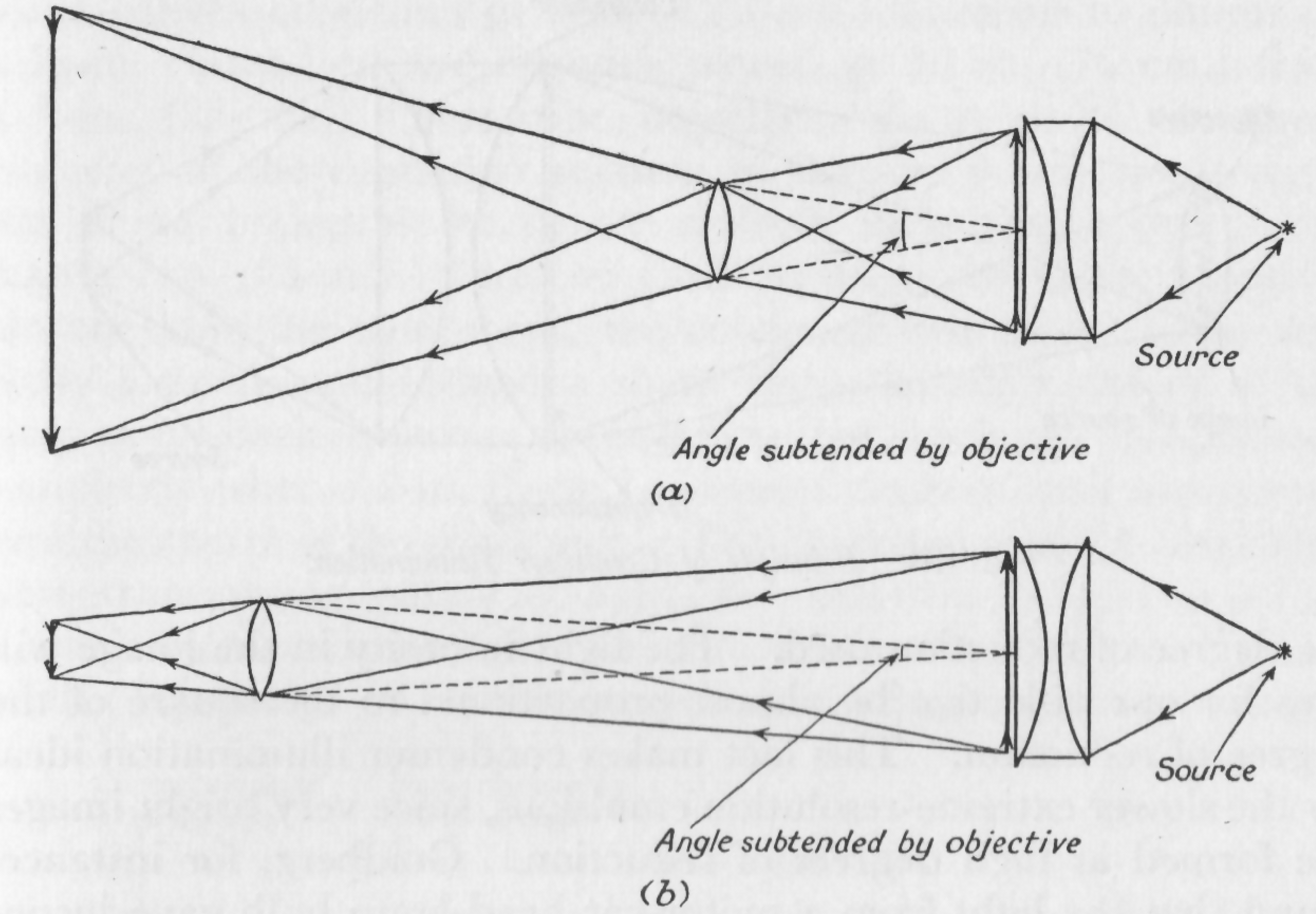


FIG. 47. *Condenser Illumination in Enlarging and Microphotography.*

When enlarging (*a*), the objective subtends a larger angle at the condenser surface than with microphotography, (*b*).

Condenser illumination for transparencies.
Illumination of transparencies through a light-scattering screen.
Diffuse illumination by reflected light.

Condenser Illumination

The principles of condenser illumination for our purpose are the same as for photographic enlarging or motion-picture projection (*Figure* 48). A condenser is used to focus an enlarged image of the light source into the aperture of the objective. When seen from the objective, the condenser should show a uniform disc of light having the same brightness as the surface of the illuminant itself. If this image just fills the opening of the objective, all the light transmitted by the transparency will be concentrated to produce a brilliant and uniformly-lit reduced image, and since the objective is effectively used at its full aperture it should give its best resolution (Chapter 5).

So long as the image of the illuminant does not over-fill the objective, all the light will be concentrated into the image, whatever

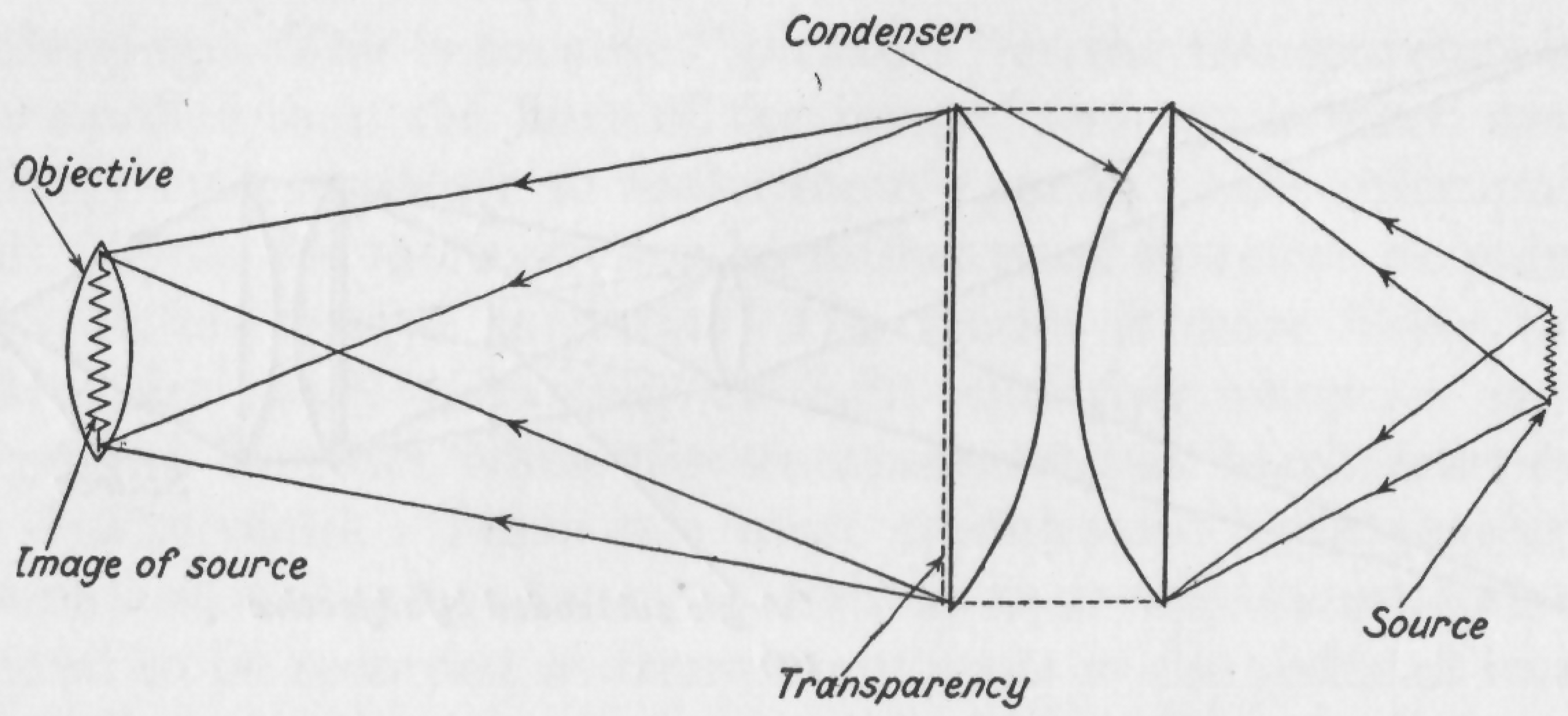


Fig. 48. *Principle of Condenser Illumination.*

the degree of reduction used. The light intensity in the image will thus for one objective be almost proportional to the square of the degree of reduction. This fact makes condenser illumination ideal for the slower extreme-resolution emulsions, since very bright images are formed at high degrees of reduction. Goldberg, for instance, found that the light from a motor-car head-lamp bulb gave inconveniently short exposures when making very minute images on his collodion print-out emulsion.(3)

A practical disadvantage of condenser illumination is that the relative positions of the light source, condenser, and objective have to be adjusted carefully to give uniform illumination over the whole field of the image. It is generally necessary to make this adjustment with the transparency removed from its holder, and even then it is advisable to check the uniformity by making a reduced image. Unless the condenser and illuminant are mounted on the negative-holder (Chapter 7), this adjustment has to be repeated every time the degree of reduction or focus is altered by moving the negative-holder along the bench. Even with this preferred method of mounting, the condenser should be re-focused, if the negative-holder is moved by more than a few per cent. of its distance from the objective.

Spherical Aberration in Condensers

Spherical aberration in condensers can be a serious problem in microphotography, particularly when images are made at high reductions with objectives having a small back aperture. This difficulty was encountered, for example, when using a double plano-convex condenser of 5 in. (12·5 cm.) diameter to illuminate a 2$\frac{1}{2}$-in. (6-cm.) square negative placed at 30 in. (75 cm.) from a 1-in. (25-mm.) microscope objective. In spite of the great diameter of the condenser relative to the size of the negative, it was found impossible to secure uniform illumination over more than a 1-in. (25-mm.) diameter circle in the centre of the negative. On checking the equipment, the condenser was found to be correctly focused, and formed a sharp image of the filament of the lamp at the back surface of the objective, but this image disappeared completely when a 2-in. (5-cm.) diameter circle of card was placed over the centre of the condenser. The outer zones of the condenser were transmitting plenty of light, but this was being focused at a much shorter distance, so that it was not entering the objective at all (*Figure* 49). The existence of such a large aberration might appear astonishing, until it is remembered that this condenser was being used in quite abnormal conditions. The condenser-to-objective distance was more than five times the distance from condenser to illuminant, whereas with normal use for this condenser the distances would have been nearly equal. The objective with which the condenser would be normally used would also have a larger opening, so that it would subtend a larger angle at the condenser and would be more likely to accept light from the outer zones of the condenser (*Figure* 47).

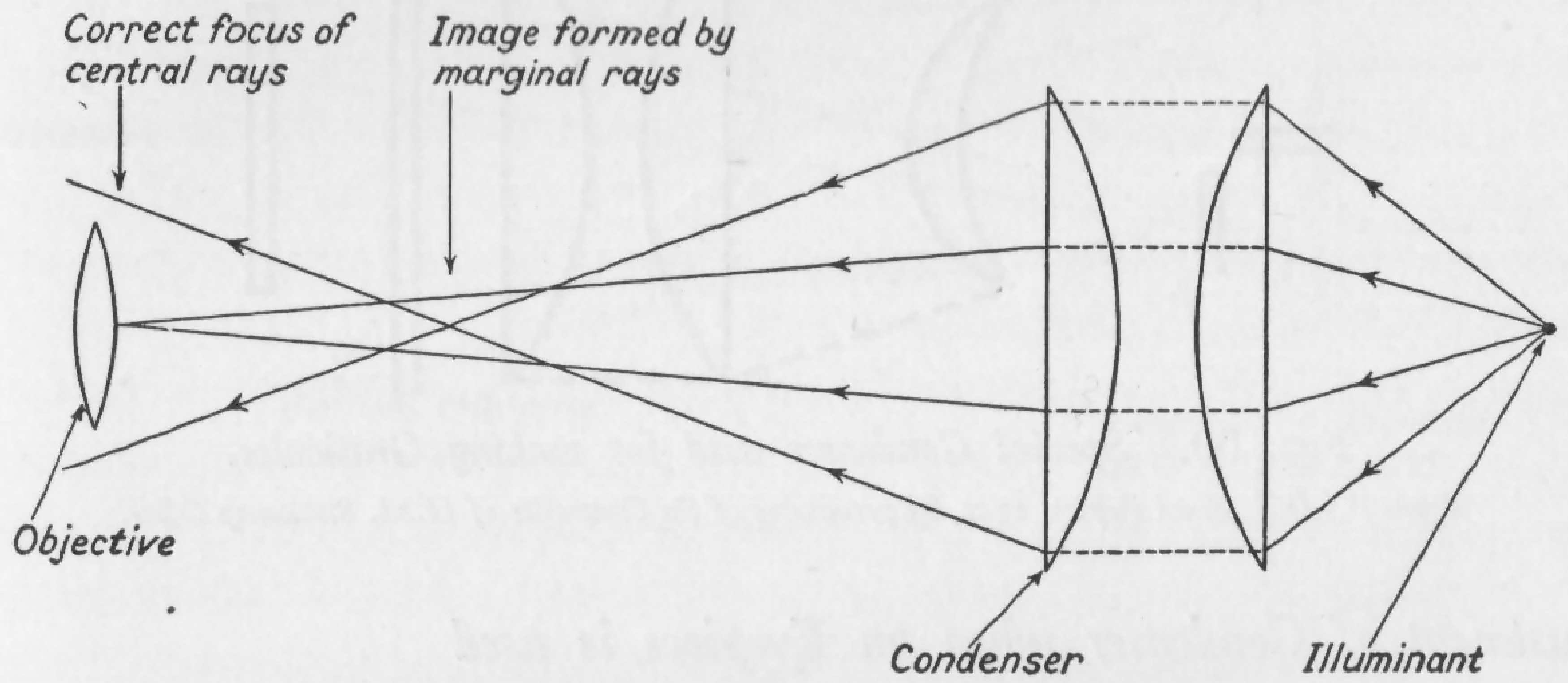


Fig. 49. *Spherical Aberration of Condenser.*

The field effectively illuminated by a condenser can be seriously reduced by spherical aberration.

A little thought shows that uneven illumination resulting from aberration of the condenser will be less apparent if the light source is of such a size that its projected image is larger than the opening of the objective. This condition leaves a margin for errors, but necessarily means that much of the light transmitted by the transparency does not enter the objective, and is wasted for image formation.

This difficulty can be avoided by the use of more elaborately constructed condensers, such as have been described by Traill Taylor (5) and Cox.(6) *Figure* 50 shows a special three-component condenser used at the Möller graticule factory,(7) whereas Sayce employed " an achromatic lens of good quality " as a condenser.(8)

(*a*) arc, (*b*) condenser, (*c*) filter, (*d*) negative.

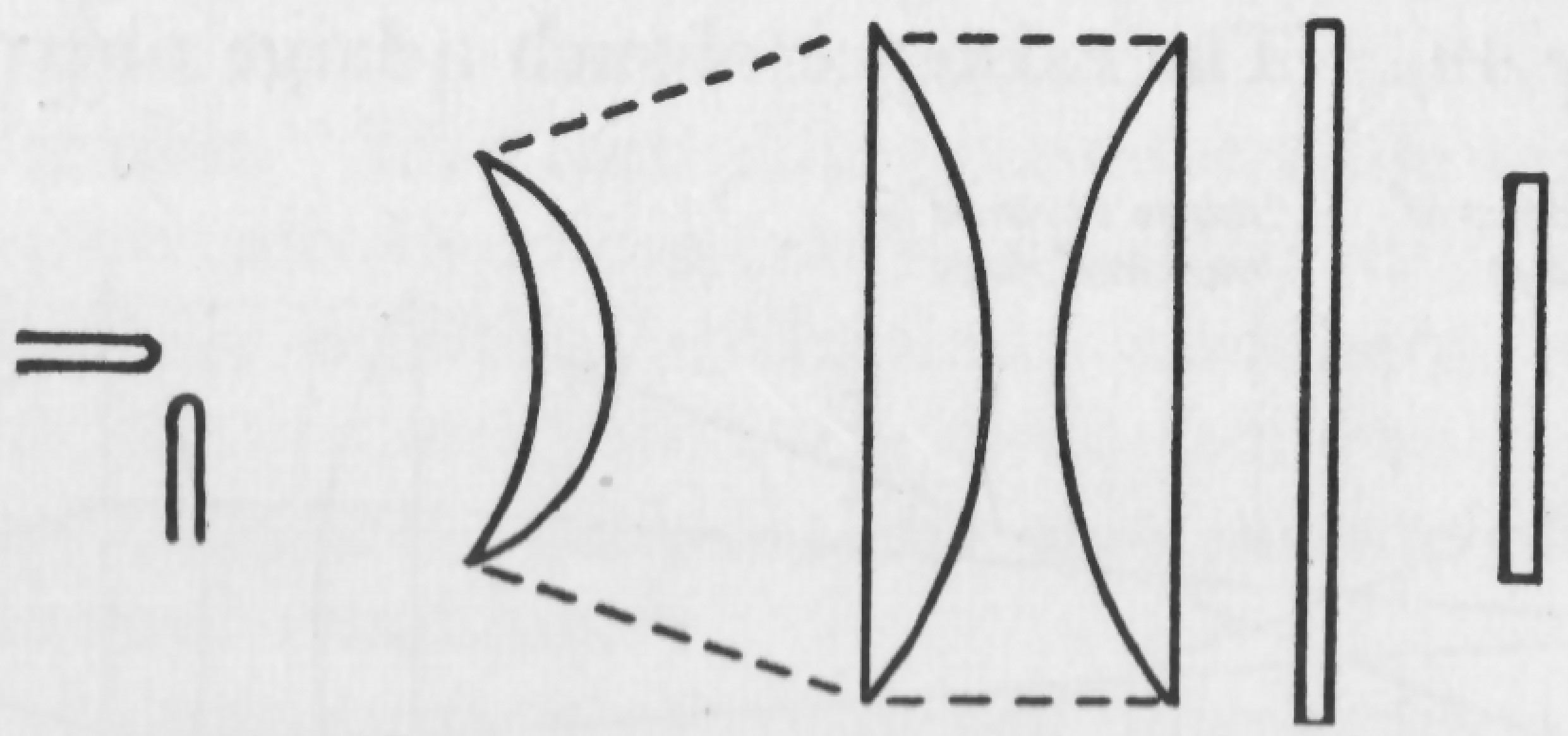


FIG. 50. *Special Condenser used for making Graticules.*

From B.I.O.S. Final Report, 1552, by permission of the Controller of H.M. Stationery Office.

Adjustment of Condenser when an Eyepiece is used

If an eyepiece is used as well as an objective for producing reduced images, all the light has to pass through a small disc situated in front of the eyepiece. This disc is, in fact, a reduced image of the back surface of the objective. Its position can be found by illuminating the objective with the sub-stage condenser, and using a piece of paper to search the space in front of the eyepiece to find the plane in which the projected disc of light is smallest. The image of the illuminant projected by the transparency condenser then has to be focused at the position found by this test. Since an eyepiece enables a given degree of reduction to be obtained with a shorter objective-to-transparency distance, it might be expected to lessen difficulties due to aberration in the condenser, but whether any real advantage will be gained depends on the immediate circumstances.

Illumination of Transparencies with a Light-scattering Screen

General Principles

In the preceding section we have seen how a condenser is used to concentrate a beam of light into the objective, so that the cone of rays from every point on the original is sufficiently wide to fill the back component of the objective. The objective can also be filled by placing a light-scattering screen between the light source and the original. With this system the exact position of the lamp

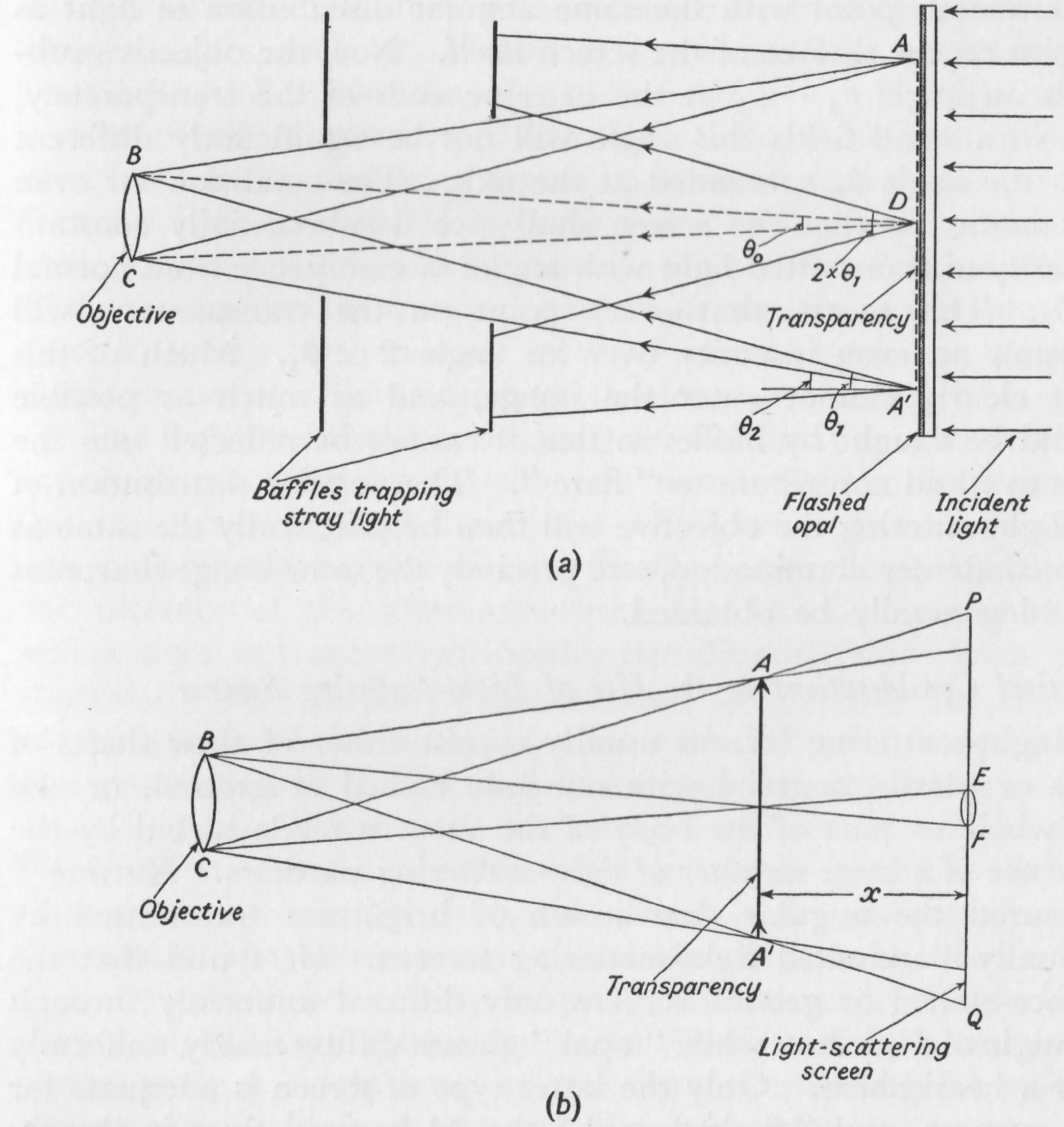


FIG. 51. *Diffuse Illumination with Light-scattering Screens.*

(*a*) Principle of diffuse illumination.
(*b*) Diffuse illumination with the screen separated from the transparency by the distance *x*.

is not particularly critical, but a much smaller proportion of the light transmitted by the transparency will enter the objective, and the brightness of the reduced aerial image will be correspondingly less. Greater latitude in adjustment is permissible with this method, but certain conditions must still be satisfied.

Let us first consider the case of a " line " transparency *AA'* (*Figure* 51*a*) placed in front of a light-scattering screen illuminated normally by a parallel beam of light. It can easily be shown that each transparent point on the original will behave as if it were a self-luminous point with the same angular distribution of light as a point on the surface of the screen itself. Now the objective subtends an angle $\theta_1 - \theta_2$ at the extreme ends of the transparency, and with small fields this angle will not be significantly different from the angle θ_0 subtended at the axis. The condition for even illumination is that the screen shall give a substantially constant intensity of transmitted light with angles of emergence from normal to θ_1. This means that every point on the transparency will transmit an even intensity over an angle $2 \times \theta_1$. Much of this light clearly cannot enter the image, and as much as possible should be caught by baffles so that it cannot be reflected into the objective and contribute to " flare ". The angular distribution of the light entering the objective will then be practically the same as with condenser illumination, and precisely the same image sharpness should generally be obtained.

Practical Considerations in the Use of Light-scattering Screens

Light-scattering screens usually consist either of clear sheets of glass or plastic material with one side etched or ground, or else the whole or part of the body of the sheet is made turbid by the presence of a large number of light-scattering particles. Nutting (9) measured the angular distribution of brightness transmitted by normally-illuminated light-scattering screens. He found that the surface-etched or ground screens only diffused uniformly through an angle of 5° or less, while " opal " glasses diffuse nearly uniformly over a hemisphere. Only the latter type of screen is adequate for our purpose, and " flashed opal " should be used since it absorbs less light than the " pot " opal.

It is clear that only a small fraction of the almost uniform hemisphere of light transmitted by each point on the screen will

enter the objective. Most of the light is thus wasted, and has to be prevented from entering the objective by diaphragms. In spite of this, sufficient intensity for the faster microphotographic emulsions can readily be obtained by using a 100-watt or a No. 1 Photoflood incandescent lamp.

The area of the screen which is uniformly illuminated need only be slightly larger than the transparency when the two are in contact ; but a larger area of uniformly-illuminated screen is required when it is separated from the transparency. In the latter case the uniformly-illuminated area of the screen must fill the space between lines such as *AP* and *A'Q*, obtained by projecting the lines *CA* and *BA'* from the edge of the objective to the most remote corners of the transparency (*Figure* 51*b*). When the screen is separated from the transparency by an appreciable distance, the image-forming light transmitted by each point of the transparency will come from a small disc of the screen, such as *EF*. Some separation of the screen from the transparency can be considered advantageous, since it lessens the tendency of small blemishes on the screen to result in uneven illumination of the image.

The brightness and uniformity of illumination given by the screen is controlled by the size and number of the light sources, and their distance from the screen. This means that the intensity can be adjusted to give a convenient exposure time by altering the distance of the illuminant from the screen : an advantage which does not occur with condenser illumination. With small sources or large distances, the intensity is inversely proportional to the square of the distance ; but with " Pearl " lamps placed at a distance of 10 in. (25 cm.) or less, the intensity is more nearly inversely proportional to the distance. To obtain tolerably uniform illumination a single " Pearl " lamp should be placed so that the distance of its envelope from the screen is at least equal to the diagonal of the transparency. Thus the distance should be 3 in. (7·5 cm.) for a 2-in. (5-cm.) square transparency. Fields larger than 6 in. (15 cm.) square are better illuminated by a number of lamps, since a single lamp at the distance required for uniform illumination is likely to give insufficient brightness.

Relative Merits of Condenser and Diffuse Illumination

With diffuse illumination the brightness of the image is almost independent of the degree of reduction. This is because both the light flux collected from any point on the transparency, and the area of the reduced image are inversely proportional to the square of the distance from the objective to the transparency. In fact, as in ordinary photography, the brightness of the image at all degrees of reduction is controlled by the angular aperture of the objective ; and the effective aperture is practically independent of the degree of reduction except when objects are photographed with small degrees of reduction. This contrasts strongly with condenser illumination, where the image intensity increases as the square of the degree of reduction. For this reason, condenser illumination is ideally suited for use with the slower extreme-resolution emulsions. There is no doubt, however, that the adjustment of condenser illumination requires an expenditure of considerable time and care, particularly if it has to be performed repeatedly during photographic focusing tests.

Diffuse Illumination by Reflected Light

Really large transparencies have been illuminated by holding them in front of a window, outside of which an inclined white screen is placed to reflect daylight through the window, but when reproducible exposures have to be given, a method using artificial light is to be preferred. The transparency may be placed over an aperture in a board supporting a bank of lamps used to illuminate a white screen (*Figure* 52). It is doubtful whether the image brilliance obtained by this method is any greater than that obtained by similarly illuminating an opaque drawing or a photographic print, but a transparency on a glass plate has the advantage of dimensional stability.

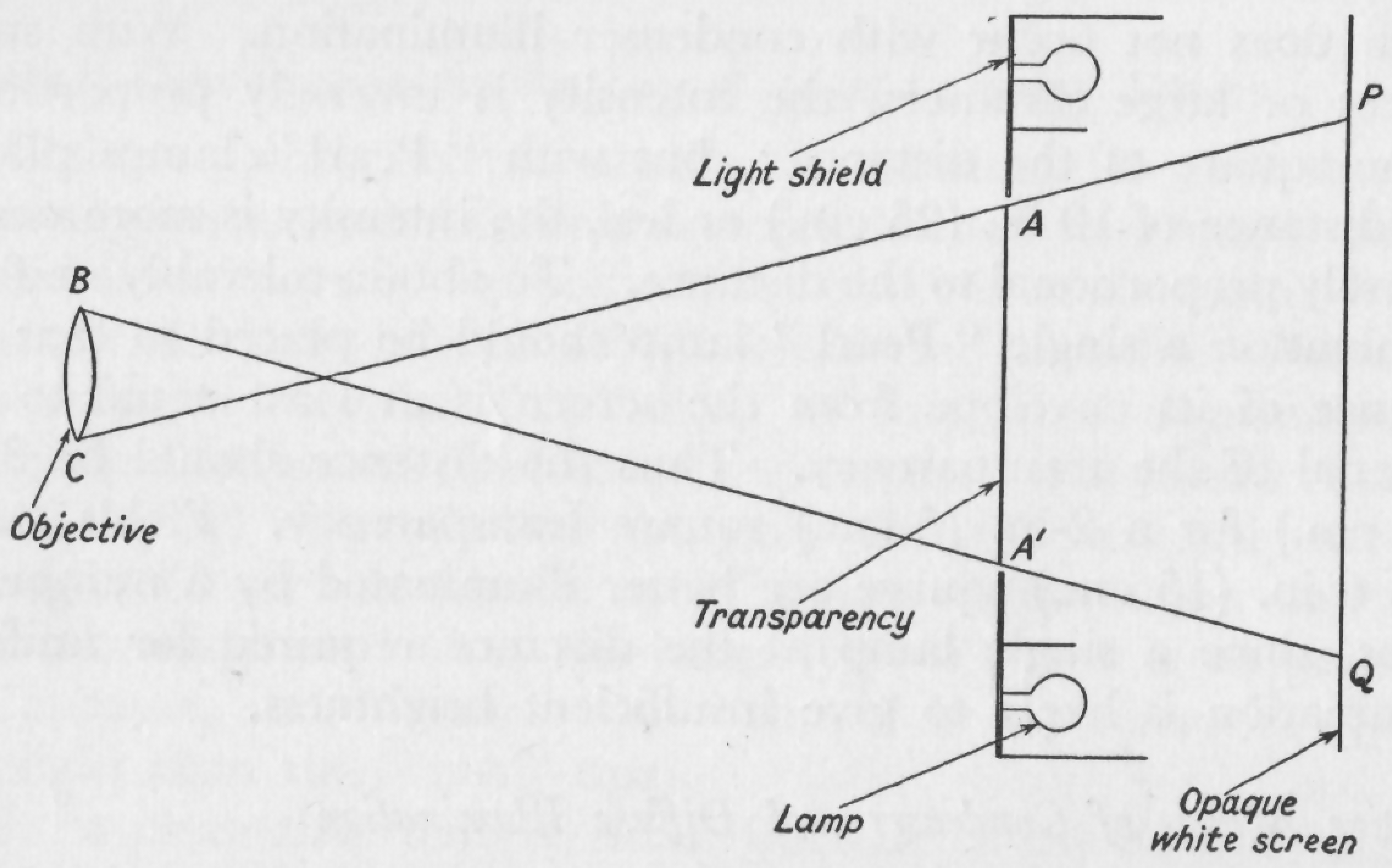


FIG. 52. *Illumination of Large Transparencies.*

The Illuminant

The choice of illuminant is determined by such factors as the spectral distribution, intensity, constancy and controllability of the light emitted, the size and shape of the source and the properties of any envelope protecting it. The spectral distribution of the light should permit adequate intensity to be obtained with the wavelengths required by the emulsion ; and it is sometimes convenient to use a source which makes it easy to expose by monochromatic light. With concentrated-Lippmann emulsions having the usual green sensitization (*Figure* 17), for instance, a mercury-vapour lamp used with a very dark-yellow filter (such as the " Wratten " No. 15) causes latent-image formation to result almost entirely from the powerful 5,460 Å. line. If light filters are used to modify the quality of the light from the illuminant, they may be placed in any position between the illuminant and the transparency, so long as they do not get damaged by heat.

A variety of illuminants giving sufficient intensity are available to-day. Overrun incandescent lamps (in particular Photoflood lamps) are invaluable for diffuse illumination, but should be handled with care since their brightness tends to fall off rather rapidly with use (Chapter 9). With diffuse illumination the shape of the filament is relatively unimportant, but ordinary domestic incandescent lamps with clear envelopes should be avoided, because striations in the glass tend to produce dark and light bands which will affect the evenness of the image. With condenser illumination, however, the lamp should have a clear envelope, since diffusion of the light defeats the whole purpose of this method. The source itself should also be so small that its image projected by the condenser can all be accepted by the objective. Filament lamps meeting this requirement fairly well can be obtained from the range of low-voltage lamps used for motor-cars, but the best source is undoubtedly the tungsten arc or " Pointolite " lamp. When ultra-violet sensitive emulsions are used, mercury-vapour lamps should be considered. Any type is suitable for diffuse illumination, but a high-pressure condensed source such as the " Mazda " (Type ME/D) is needed to obtain the full advantage of condenser illumination.

On completing this section, one is tempted to wonder how the earlier microphotographers achieved their excellent results with the crude illuminants available at the time. The inconvenience caused by their illuminants was overcome with patience and ingenuity. Dancer, for instance, used a paraffin lamp and increased his rate of production by using two microphotographic cameras simultaneously, one on either side of the lamp !(10) The modern worker can be thankful that he is not reduced to such devices, but can concentrate his skill on developing further refinements or applications for his art.

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CHAPTER 9

Microphotographic Technique

IN THIS CHAPTER we shall consider the decisions which have to be made and the procedure to be followed in making microphotographic images. In doing this we shall assume that all necessary materials and apparatus are freely available, so that our conclusions will be determined only by the requirements of the images, and will not be restricted by questions of supply. In practice, of course, it may often be necessary to compromise and obtain the best result given by available equipment.

For convenience the present chapter is divided into three sections. The first describes how the component parts are selected for making any particular image, the second deals with the phenomenon of image formation, and the last with establishing and maintaining the conditions needed to give a satisfactory image.

Selection of Components

The components which have to be collected before making any microphotograph are the sensitive material, the objective, the focusing mechanism, the original transparency and the illuminating system. Selection of these components should not be done in isolation, but all should be chosen to suit the requirements of each particular job, so that their functions interlock to give a coherent working system. It is therefore helpful to consider the different components in a definite sequence, such as the following :

(1) Specify the line width and field to be covered in the microphotograph, and select an *objective* likely to give the performance required.
(2) From the focal length of the objective deduce the degree of reduction required, and hence decide on the *size of the original negative.*

(3) Select an *emulsion* to give the line width and contrast and any other image properties which may be required.
(4) Choose an *illuminating system* suitable for use with the selected emulsion, objective and size of original negative.
(5) Choose a *focusing mechanism* having the precision required by the selected objective.
(6) Choose *processing conditions* suitable for the emulsion, the image contrast and any special properties needed.

The factors influencing these decisions have already been discussed in preceding chapters, but the reader must always remember that each component may influence the performance of several others. This system of interactions can be visualized diagrammatically by placing the components in the centre (components are underlined in *Figure* 53), and arranging the more important requirements around them (in boxes). The interactions are shown by arrows against which are placed the operating factors. This diagram is useful in that it shows that the components should never be chosen in isolation, and it can also be helpful in tracing troubles.

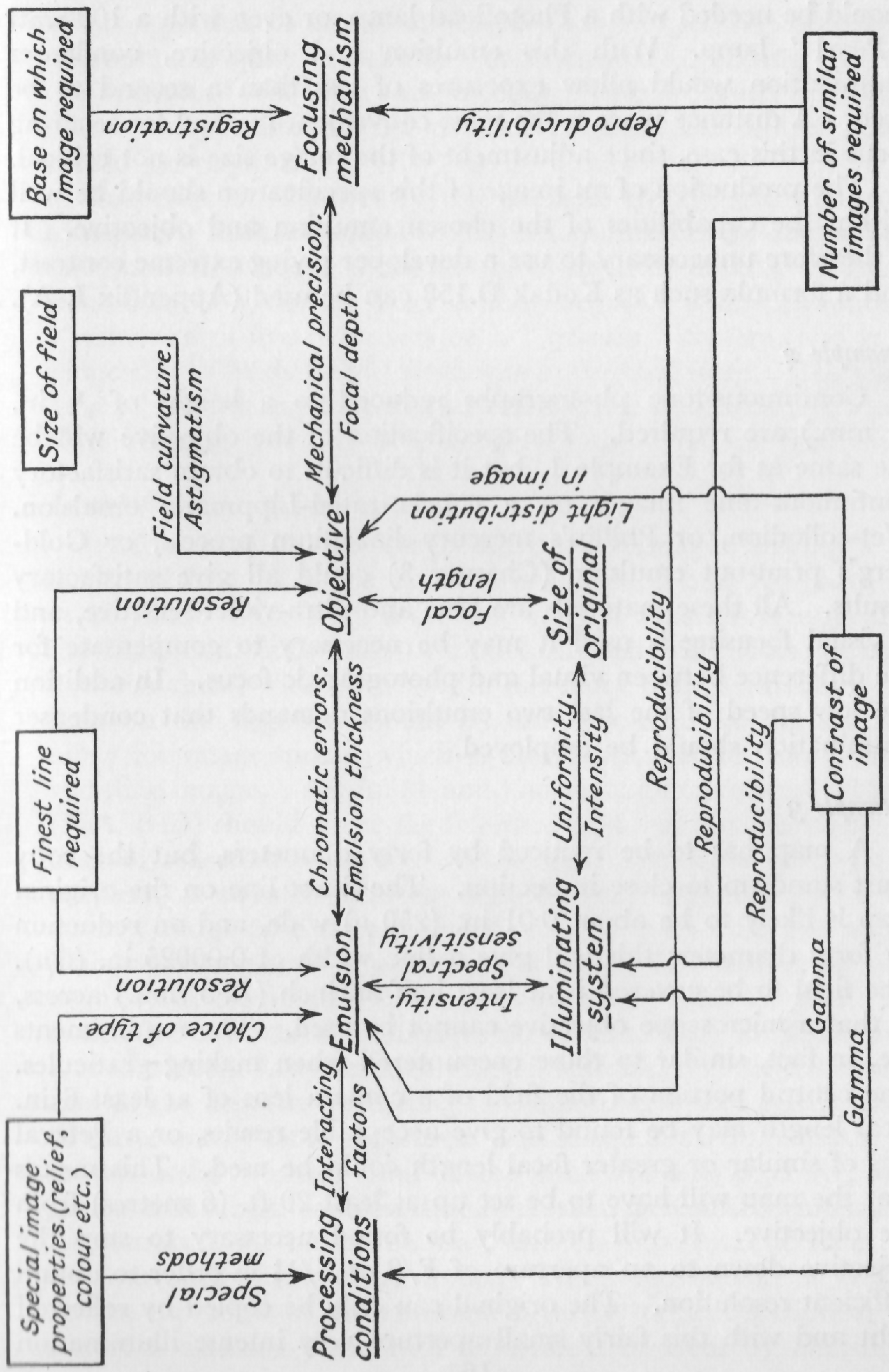
The way in which the components are chosen will now be illustrated by a few examples, illustrating the different choices required by varying circumstances.

Example 1

Microphotographs are required of a page with 40 lines of print reduced to a height of $\frac{1}{25}$ in. (1 mm.). The height of the small letters will be about 0·0003 in. (8 μ), and a line width less than one quarter of this figure will be needed. This line width can be obtained over the required field with a 1-in. (25-mm.) or $\frac{2}{3}$-in. (16-mm.) achromatic microscope objective. A reduction ratio of 35 diameters with these objectives will require convenient working distances of about 35 or 22 inches (87 or 55 cm.) respectively, and the intermediate negative can be made on 35-mm. film.

Plates coated with a concentrated-Lippmann emulsion will easily give the necessary resolution, and have a spectral sensitivity well adjusted to the performance of an achromatic objective.

The small original negative can be illuminated satisfactorily with a tungsten lamp placed a few inches from a flashed opal behind the negative, and an exposure time of less than a minute



Base on which image required
Registration
Focusing mechanism
Reproducibility
Number of similar images required
Size of field
Field curvature. Astigmatism
Mechanical precision. Focal depth
Light distribution in image
Resolution
Objective
Focal length
Size of original
Reproducibility
Finest line required
Chromatic errors. Emulsion thickness
Uniformity. Intensity
Reproducibility
Contrast of image
Spectral sensitivity
Resolution
Intensity.
Choice of type.
Emulsion
Illuminating system
Reproducibility
Gamma
Gamma
Special image properties (relief, colour etc.)
Special methods
Processing conditions
Interacting factors

FIG. 53. *Interaction of Requirements and "Components".*

should be needed with a Photoflood lamp, or even with a 100-watt "Pearl" lamp. With this emulsion and objective, condenser illumination would allow exposures of less than a second to be used. A distance piece is the most convenient method for securing focus in this case, since adjustment of the image size is not critical.

The production of an image of this specification should be well within the capabilities of the chosen emulsion and objective. It is therefore unnecessary to use a developer giving extreme contrast, and a formula such as Kodak D.158 can be used (Appendix I, A).

Example 2

Continuous-tone photographs reduced to a height of $\frac{1}{25}$ in. (1 mm.) are required. The specification of the objective will be the same as for Example 1, but it is difficult to obtain satisfactory continuous-tone images on a concentrated-Lippmann emulsion. Wet-collodion, or Phillip's mercury-diazonium process, or Goldberg's print-out emulsion (Chapter 3) could all give satisfactory results. All these materials are blue and ultra-violet sensitive, and if visual focusing is used it may be necessary to compensate for the difference between visual and photographic focus. In addition the low speed of the last two emulsions demands that condenser illumination should be employed.

Example 3

A map has to be reduced by forty diameters, but the copy must stand up to close inspection. The finest line on the original map is likely to be about 0·01 in. (250 μ) wide, and on reduction by forty diameters this will give a line width of 0·00025 in. (6 μ). The field to be covered is at least half an inch (12·5 mm.) across, so that a microscope objective cannot be used. The requirements are, in fact, similar to those encountered when making graticules. The central portion of the field of a camera lens of at least 6 in. focal length may be found to give acceptable results, or a Petzval lens of similar or greater focal length could be used. This means that the map will have to be set up at least 20 ft. (6 metres) from the objective. It will probably be found necessary to stop the objective down to an aperture of F/8 or F/11 in order to obtain sufficient resolution. The original can only be copied by reflected light and with this fairly small aperture very intense illumination

will be needed to avoid an unduly long exposure. The fastest microphotographic emulsions (concentrated-Lippmann plate or wet-collodion) will have to be used, and with arc lamps or illumination by direct sunlight an exposure of less than fifteen minutes should be required.

Inconvenient features of this method are the great objective-to-negative distance and the low image brightness obtainable at the emulsion surface. Both can be avoided by making a two-stage reduction, in which an intermediate negative is first produced at a reduction of five diameters on a "process" camera, and is then reduced by a further eight diameters in the final stage. The smaller area of the intermediate negative facilitates production of a really bright image, resulting in a shorter exposure for the final images.

Example 4

A few specially fine stage micrometer images, having a total length of 0·2 mm. (approx. 0·008 in.) divided into 100 parts, have to be made. For such a scale to have a satisfactory appearance the individual lines must be noticeably narrower than the spaces between them, with a line width not more than 0·5 micron. The lines on the negative should be only one-tenth of the spaces, to allow for image spread which is always appreciable when making very fine images. A $\frac{1}{6}$-in. (4-mm.) achromatic microscope objective (N.A. 0·65) should cover the 0·2-mm. field and give an image with lines of reasonable quality. When used without a cover-glass or eyepiece, a suitably selected objective was found to give a satisfactory image at a distance of 20 in. (50 cm.) from the original. This corresponds to a reduction of about 120 diameters, and a negative approximately 1 in. (25 mm.) long may be used. If it is decided to make these images on commercially available plates, a concentrated-Lippmann emulsion is suitable, and diffuse illumination of the negative with tungsten illumination will permit the use of conveniently short exposures. An image of such fineness is close to the useful working limit of the emulsion and objective, which means that a high-contrast developer, such as Kodak formula D.178 (Appendix I, A) should be used, and the exposure and focus must be controlled within small limits. The image should be confined to the top third of the emulsion layer by optical sectioning, and use of a distance piece with adjustment of focus by altering the distance of the negative will give the necessary precision. The precise length of the scale will thus have to be adjusted by altering the size of the intermediate negative. Goldberg's collodion print-out emulsion could also be used, but might give little improvement of sharpness because the lower contrast is likely to lessen the advantage of its finer grain.

When starting to make microphotographs the reader is recommended to record his choice of components in a diary. The very act of writing all the information down tends to prevent the forgetting of important details, and helps in the tracing of troubles when practical work is actually started. Such notes are a great help in the working up of a satisfactory technique.

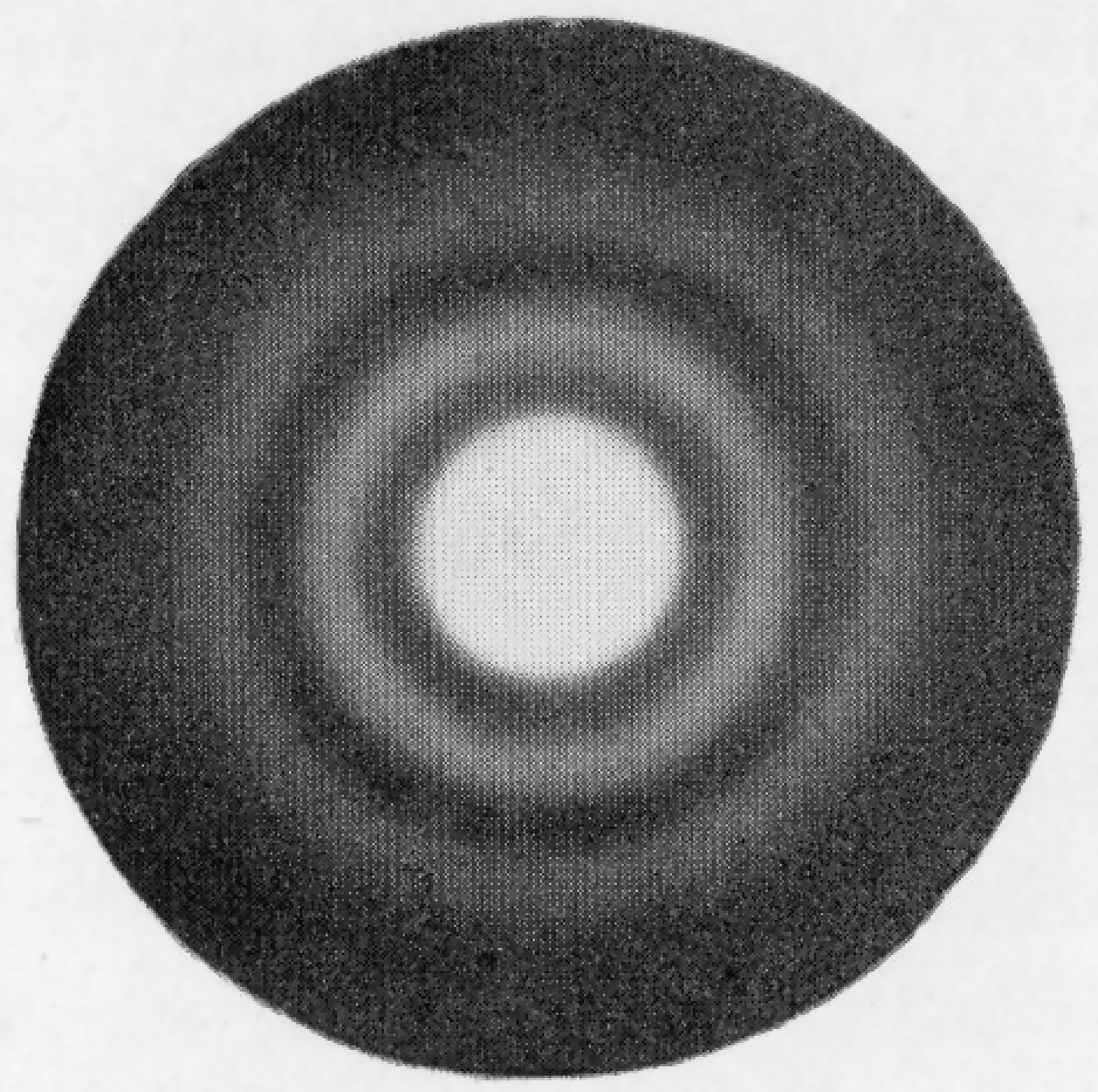
The Phenomena of Image Formation

While good results can be obtained by purely rule-of-thumb methods, an understanding of the process of image formation is likely to allow satisfactory results to be obtained with greater speed and certainty. This knowledge will permit the reader to visualize what has actually happened in the emulsion layer during the exposure, and this is particularly useful when the work is not going well, and puzzling results are being obtained. The source of the trouble can in favourable cases be deduced from a careful inspection of the image, thus saving hours or days of effort in trying to correct the fault empirically.

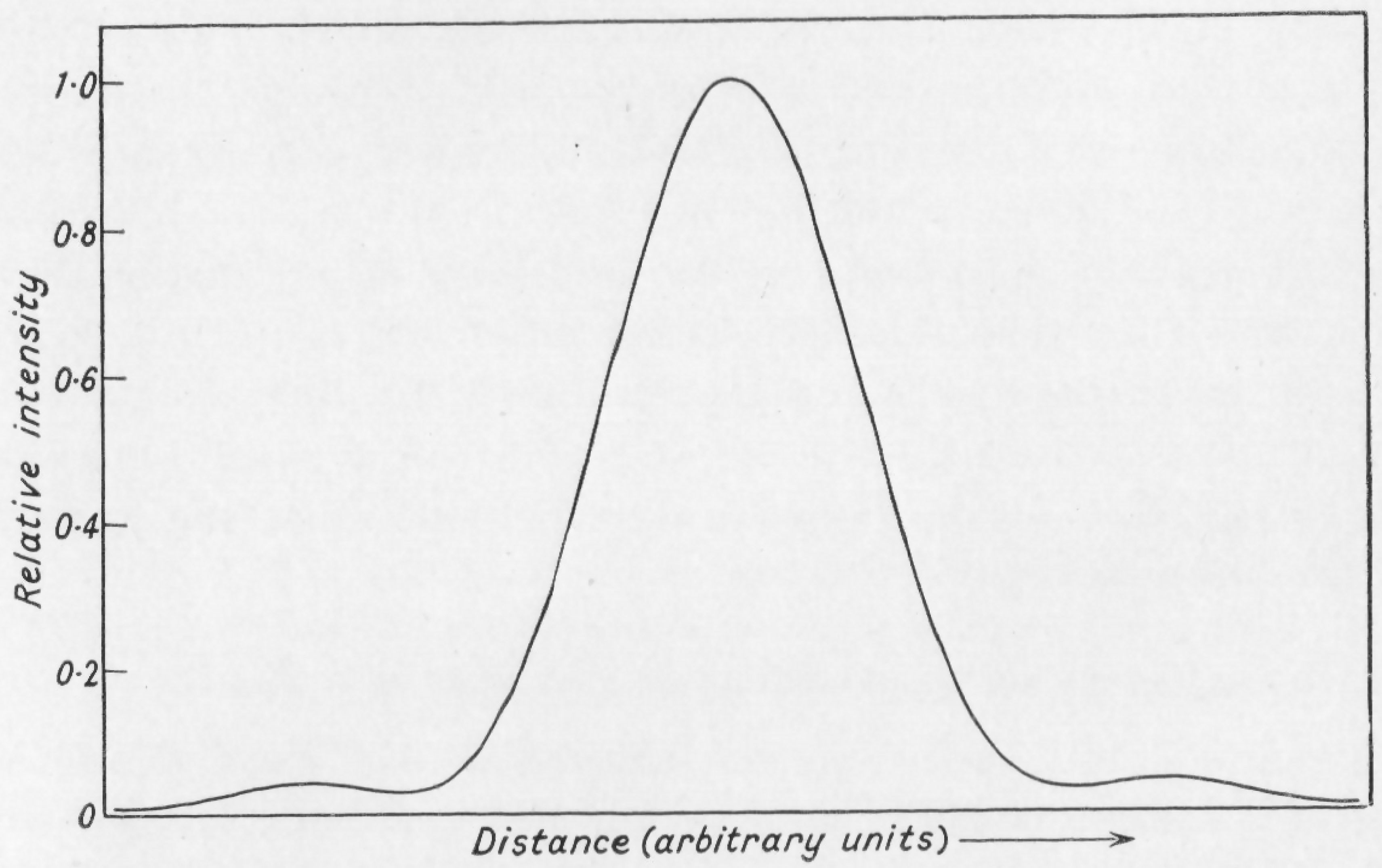
Image Formation in the Focal Plane of a " Perfect " Lens

The image of a point source formed in the focal plane of a " perfect " lens is never a true point, but the light is spread out into a diffraction pattern known as the Airy disc (*Figure* 54*a*). This means that the brightness and sharpness of very small images is less than would be anticipated from purely geometrical concepts of image formation. Now a line can be thought of as a large number of points side by side, and the light distribution in its image can be computed by dividing the Airy disc into narrow bands parallel to the line, and integrating the total light flux inside each of these bands. *Figure* 54*b* shows the intensity profile of a line plotted from figures calculated in this way by Selwyn.(1)

The fact that the image of an " infinitely fine " line possesses a finite width and unsharpness is the physical reason for the resolution



(*a*) Representation of " ideal " Airy disc.



(*b*) Intensity profile of line image resulting from overlapping of many Airy discs.

FIG. 54. *Airy Disc and Intensity Profile of Line Image.*

limit of perfect objectives. When the centres of two parallel lines are brought so close together that their images overlap, the intensity profile of the pair can be simply calculated by summing the point-to-point contributions of light from both images. *Figure* 55 shows

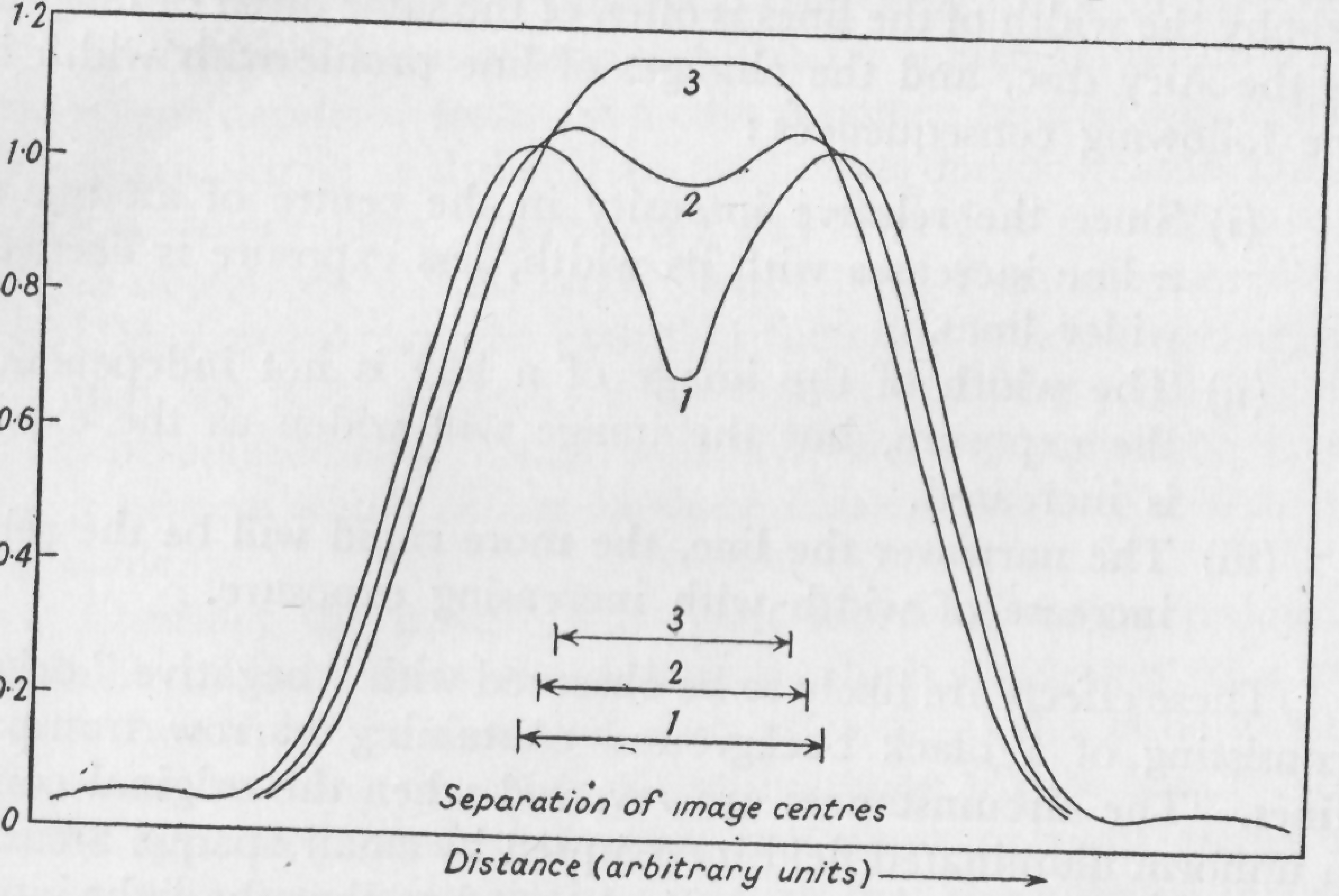


FIG. 55. *Profiles of Pairs of Lines at the Limit of Resolution.*

The composite profiles for pairs of lines have been calculated by adding the light intensity derived from each. Three cases are shown for separations indicated by the arrows. Note how rapidly the density depression between the images decreases with reduced separation.

a number of such composite profiles for pairs of lines separated by $4\frac{1}{2}$ units of distance (curve 1), 4 units (curve 2) and $3\frac{1}{2}$ units (curve 3). Curve 1 shows that the close proximity of the two lines has resulted in extensive filling of the intensity " valley " between them. The small extra approach of the two lines corresponding to curve 2 results in almost complete filling of the valley, and an even closer approach with curve 3 gives a profile showing no depression at all between the two peaks. In fact, there is a critical separation of the two lines, below which there is no reduction in the light intensity between their centres, and resolution in the sense of direct recognition of the existence of two lines is then physically impossible.

In the same way that the intensity profile of a fine line can be calculated by considering the result of overlapping a large number of Airy discs in a single row, the profile of wider lines can be computed by considering the overlapping of many parallel rows. This reasoning shows that the intensity of the projected images of lines increases with their width, until the width is large compared with the Airy disc. In extreme-resolution microphotography the width of the lines is often of the same order of magnitude as the Airy disc, and the changes of line profile with width have the following consequences :

(i) Since the relative intensity in the centre of an image of a line increases with its width, less exposure is needed for wider lines.

(ii) The width of the image of a line is not independent of the exposure, but the image will widen as the exposure is increased.

(iii) The narrower the line, the more rapid will be the relative increase of width with increasing exposure.

These effects are likely to be observed with " negative " originals consisting of a black background containing narrow transparent lines. The circumstances are reversed when the original contains a uniform illuminated field interrupted by small opaque areas. In fact, the three consequences are changed so that the light intensity in a line *decreases* with width, the images become *narrower* with increasing exposure, and the relative rate of *narrowing* is greatest for the finest lines.

Image Formation by Lenses with Appreciable Aberration

In the case of other than " perfect " lenses the diffraction pattern of the Airy disc is modified by spherical or other aberrations. This usually results in a further widening of the patch of light from the image of a point source, and alters the intensity profile of the image. Sometimes the image may consist of a bright annular ring, or may take the form of a bright central spot surrounded by a disc of flare light. In the latter case the image can usually be sharpened by stopping the objective down. So long as the objective is correctly centred, the axial image of a point source will still consist of a circular illuminated disc, and the intensity will still increase with line width. In addition, the rate of broadening of a line with increased exposure is, when aberrations are present, likely to be more rapid than with a perfect lens.

Image Formation in an Emulsion

The phenomena described in the preceding sections are all concerned solely with the aerial image. It is now necessary to consider what happens when an image is projected on (or into) an extreme-resolution emulsion. The first thing to note is that the effective thickness of most industrially coated emulsions is greater than the depth of focus of medium-power microscope objectives. In particular it is difficult to coat silver-halide-gelatin emulsions to give a dry layer appreciably less than 5 μ (0·0002 in.) thick. With objectives of N.A. larger than 0·3 (or F-numbers smaller than 1·7), this means that the emulsion thickness is no longer negligible, so that the path of the rays on each side of the focal plane must also be considered. Image formation must therefore be examined as a process which occurs in three dimensions, rather than just in a plane.

Consider the image of a point source as being produced by a cone of light from the objective which converges to a point,* and then diverges to make a second cone of the same angle with its apex touching the apex of the first cone (*Figure* 56*a*). Now the total light flux passing through any plane at right angles to the axis of the lens must be the same, so that the average intensity in any plane must be inversely proportional to the cross-sectional area of either cone where it is cut by the plane. The intensity is thus highest in the focal plane where the apexes meet, and falls off rapidly on each side. The counterpart of this phenomenon can be readily observed in microscopy with dark-ground illumination, where the rapid falling off in the brightness of small objects on each side of the plane of focus is known as " optical sectioning ".

We can now examine the result of projecting the image of a point source into a relatively thick and optically-clear dry-plate emulsion. In cases 1 and 4 (*Figure* 56*a*) the cones only fall in the emulsions at positions where their areas are large, and the intensity is therefore relatively low. In cases 2 and 3 the apexes of the cones are formed inside the emulsion. If the contrast of the emulsion is high, and no more than the minimum necessary

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* This is a purely geometrical picture of image formation which neglects the wave theory of light, but the physical reality of the cones is illustrated by *Figure* 62. In any case the qualitative validity of our conclusions is not lessened by this simplification.

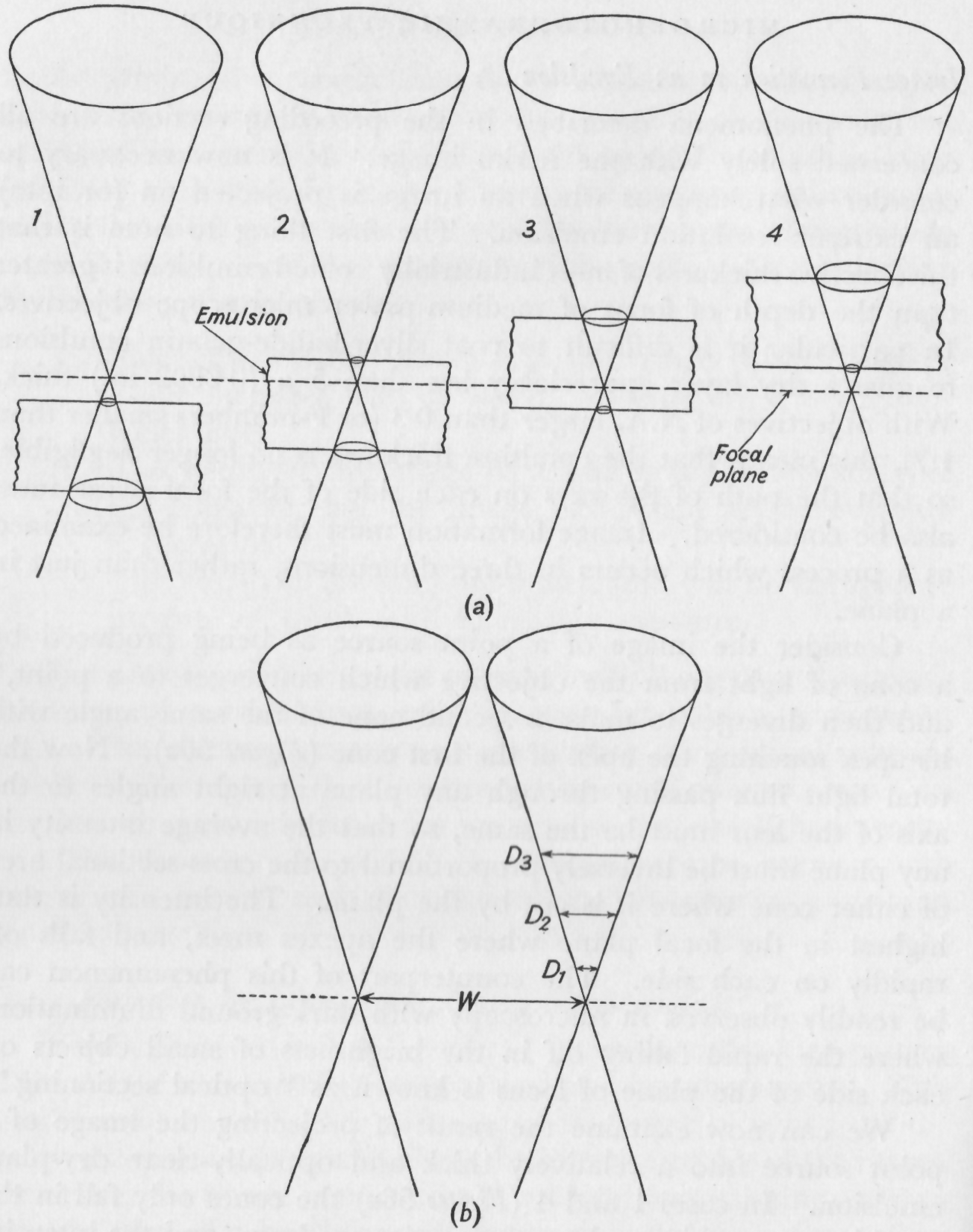

FIG. 56. *Optical Sectioning in Microphotography.*

(*a*) *With a point source.* The intensity in any plane is inversely proportional to the cross section of the cone in that plane. Thus cases 2 and 3 result respectively in images near the surface and near the bottom of the emulsion, and give higher densities than cases 1 and 4.

(*b*) *With lines of varying width.* Formation of image of a wide line. The length of the line (at right angles to the paper) does not change significantly with exposure. Thus the intensity is inversely proportional to the total width, i.e. $W + D_1$, $W + D_2$, $W + D_3$ . . .

exposure is given, appreciable blackening will only be produced for a very short distance above or below the apexes. In fact, an image may be formed by " optical sectioning " at any level in the emulsion, and photographic-focusing tests often give quite sharp images definitely confined to the lower part of the emulsion (Chapter 10).

These changes in the intensity of the image of a point source on each side of the focal plane mean that the density of a small image will depend on the focus as well as on the exposure time and on the intensity of the illuminant. The magnitude of the intensity decrease in out-of-focus planes is proportional to the increase of the area illuminated, and the rate of increase of the area depends on the shape and size of each element of the image. A rough estimate of the increase in the illuminated area can be made by considering all images as consisting of large numbers of points, with the cones corresponding to adjacent points overlapping during image formation. With a really fine line, which can be regarded as a single row of points, it can readily be shown that the increase in the illuminated area in any out-of-focus plane will be proportional to the diameter of the cone, and not (as in the case of a point) to its cross-sectional area. The reduction of density on each side of the focal plane will hence be less rapid than in the case of a point. Wider lines can be considered as several rows of points lying side by side. A cross section (*Figure* 56*b*) shows that the area will now increase less rapidly than the diameter of the cone. In fact, if W is the ideal width of the image of a line and D is the diameter of the cone in any plane, the relative intensity in different planes will be given by:

$$I \propto \frac{W}{W + D}$$

Thus the greater the width of the line, the less rapidly will the intensity decrease in out-of-focus planes. These differences mean that a larger proportion of the emulsion thickness will contribute blackening to the image of a wide line than to the image of a narrow line.

In practice, the phenomena accompanying image formation may not be so straightforward as has been indicated by this idealized picture. Thus any aberration in the objective will tend to blunt the cones of light, so that these become connected by a region whose thickness changes little for some distance on each side of the geometrical focal plane (see *Figure* 62). In effect, an increase in the depth of focus is obtained at the expense of a loss of resolution. The phenomena of image formation will also become less clear-cut if the emulsion scatters light, and conditions are further changed by light absorption in the emulsion. These complications only modify the details of the process, but do not prevent effects of this type from influencing the production of microphotographs. The simplified models are, in fact, of great assistance in visualizing the physical processes of image formation.

Influence of the Sensitometric Properties of the Emulsion

The present discussion has, so far, only been concerned with the distribution of light in the optical image. The resultant distribution of density in the photographic image is also influenced by the characteristic curve of the emulsion used. Thus quite different conditions are obtained when the same final image is produced by a process giving either a " direct-positive " or a " negative " rendering. An image consisting of fine dark lines on a clear background can, for instance, be made by exposing an emulsion, giving a " negative " rendering, to an original consisting of fine clear lines on an opaque background. The line width will then *increase* with the exposure, and as only a very small proportion of the field is illuminated, the effect of lens flare is likely to be small. A similar image can be obtained by using a " direct-positive " process to copy a transparency with fine black lines on a clear background, but the line width will then *decrease* with the exposure, and the high proportion of the field which is illuminated means that flare may have a substantial effect. On the other hand, flare is likely to be less troublesome when a direct-positive emulsion or process is used to copy a " negative " transparency. In Chapter 3 it was also noted that use of a high-contrast emulsion can effectively increase the image sharpness by producing a steep density profile from a flat intensity profile (*Figure* 19).

Establishing a Satisfactory Image

There is one dominant requirement which all the devices of microphotographic technique must attempt to satisfy : it is that

the reduced copy of the original should show the minimum increase in the relative thickness of the lines. Ideally the thickness of the lines should equal their thickness in the original divided by the degree of reduction, but this is a degree of perfection which can only be approached when making images of a size well within the capabilities of the emulsion and objective. When using an original consisting of an opaque plate with small transparent areas, the width of the lines in the reduced image normally increases with increasing exposure, and this indicates that the correct exposure is the least which gives adequate density (or transparency in the case of a direct-positive process) in the finest lines. If the image also contains wider lines, they are likely to be thickened by the increased exposure needed for the fine lines. Solutions to this problem are discussed in Chapter 8.

In practice the correct exposure cannot be determined until the objective is correctly focused, since with " negative " processes the density of fine lines given by a definite exposure decreases rapidly when the objective is put out of focus. One must, however, also determine approximately the correct exposure in order to execute a sensitive photographic-focusing test. Too heavy an exposure will cause even a sharply-focused image to appear unsharp, and thus blunt the discrimination of the test. The establishing of a satisfactory image has therefore to proceed by a series of successive approximations in which an exposure test is made at an approximate focus, followed by a focusing test at the best exposure indicated by the first test. These tests clearly cannot be executed satisfactorily without adequate exposure control, because uncontrolled changes of exposure level can result in confusing changes of image quality.

Exposure Control

Before considering methods of exposure control in detail, it should be noted that the effective speed of developing-out emulsions is markedly affected by development conditions, and this is particularly true for such fine-grain materials as the concentrated-Lippmann emulsions (Chapter 4). Careful exposure control is thus useless if random variations of development time or temperature are permitted, or if the developer is allowed to get stale. It should also be realized that all photographic materials may show small differences of speed from batch to batch. The exposure tolerance in microphotography is often likely to be smaller than the batch-to-batch speed variations, and a fresh exposure test for the production of any particular image should therefore be made with each batch of plates.

The factors which can be used to control the exposure are :

the illuminant and the optical system with which it is used,
any light filter used to modify the spectral quality or intensity of the light,
the distance from the illuminant to the original (when diffuse illumination is used),
the current passing through the lamp,
the exposure time.

The usual practice is to use the first four factors to obtain a convenient intensity of illumination, and then vary either the lamp current or the exposure time. With diffuse illumination large changes of intensity can conveniently be made by varying the distance from the lamp to the diffusing screen. Once a convenient intensity level has been determined, the distance should be kept constant, since any accidental change will necessitate another exposure test. The maintenance of the same lamp distance requires particular care when the focusing tests are made by moving the original to and fro on the optical bench, rather than by moving the objective relative to the emulsion. In the former case the lamp should preferably be firmly attached to the base of the negative-holder, so that its distance from the original is not changed when the negative-holder is moved (Chapter 7).

Variation of the current or voltage of an incandescent-tungsten lamp is a useful means for making small adjustments of exposure, and is particularly convenient when a mechanical shutter is used to give a fixed exposure time. The most certain method is to use an ammeter in series with the lamp, since inaccurate readings due to poor contact in the lamp-holder are avoided. Whether the current is controlled by an ammeter or a voltmeter, the instrument used need not be particularly accurate, but should give a large deflection of the needle while the lamp is burning. This should make it possible to reproduce the current or voltage within plus or minus one per cent., and thus obtain consistent exposure conditions. Control of the lamp current can alternatively be used to

guard against changes in mains voltage, or to maintain a constant light emission as measured by a photocell. This type of precaution is most likely to be needed when using a high-contrast material such as a concentrated-Lippmann emulsion.

Selection of an appropriate exposure time is a simple and sensitive method of adjusting the exposure to the desired level. When making continuous-tone pictures, or using a low-contrast emulsion, a sufficiently correct exposure can usually be found by a test in which the exposures are successively doubled. This procedure may not always prove sufficiently sensitive for high-contrast emulsions, and the following method is recommended.

First adjust the intensity of the illumination so that an exposure time of at least ten seconds will be needed. When the exposure is given by hand, this is the shortest time which is likely to give the consistency needed by the high-contrast emulsions. Make a widely spaced series of exposures such as 1, 3, 10, 30 and 100 seconds, and develop the test plate. If this first test indicates an exposure between 10 and 30 seconds, make a second test with a more closely spaced series such as 10, 14, 20 and 28 seconds, or 10, 12, 14, 17, 20, 24 and 28 seconds.* If the first test indicates an exposure outside these convenient limits, it is advisable to adjust the intensity of illumination.

Determination of the Best Combination of Exposure and Focus

The best combination of exposure and focus can only be ensured by a series of interlocking photographic-exposure and focusing tests made with equipment permitting the conditions to be strictly controlled. Such a procedure permits the effect of any change to be assessed in terms of its influence on the final result, and this must provide the most certain route to a satisfactory image. When a few images of only moderate fineness are required, visual focusing can be used, and it is then only necessary to make one test to determine the exposure time. Visual focusing to the required accuracy is, however, a highly skilled task, and may give disappointingly variable results. This criticism does not apply to Goldberg's split-beam technique (Chapter 6, *Figure 31b*), but his method is only suitable for very slow emulsions and for the making of fairly small numbers of images.

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* See Appendix III on " Series of exposure times ".

The operation of an interlocking exposure and focusing test at first seems most laborious, but it has been found that the following system rarely fails to give satisfactory results within two hours: a fraction of the time which can be wasted by random muddling.

(1) Focus the objective visually, by using a magnifier focused on the plane of the negative-holder to observe an enlarged image projected from a test plate in the image plane (Chapter 6). The focus should now be sufficiently correct to permit the production of a really informative exposure test.

(2) Make a rough exposure test, with large increases of exposure time or lamp current between one exposure of the series and the next. On development this plate should be used to judge the focus as well as to determine the approximate exposure needed.

(3) At this juncture at least three courses of action are possible:

  (*a*) If any of the images of the first exposure test are *really* sharp, it may only be necessary to make a further exposure test with the time or lamp current changed by smaller increments.

  (*b*) If the images in the first test are *fairly* sharp, it may be thought advisable to make a further test to determine the optimum exposure for stage 4.

  (*c*) If the images are obviously unsharp, estimate the exposure likely to be needed in stage 4. Remember that more critical focusing will increase the density of fine lines as well as their sharpness.

(4) Unless the sharpness of the images given by the exposure tests is irreproachable, make a series of exposures with the focus changed by small increments (Chapter 6), and at the exposure indicated by stage 3.

If all goes well, stage 4 should give images of such quality that no further tests are deemed necessary. Really critical work or the need for a large number of images may, however, merit the making of confirmatory tests.

(5) The first confirmatory test will be another exposure test at the optimum focus indicated by stage 4.

(6) The second confirmatory test will then take the form of another focusing test at the exposure indicated by stage 5.

This last test should show not only whether the image is sharp, but also at which level in the emulsion it is formed.

If the components have been wisely chosen for the job, this systematic procedure should go smoothly with few hitches. The successive test images should, however, also be watched for signs of an incorrect choice or any lack of adjustment in the equipment. Thus an inability to record fine and less fine lines with the same exposure may have to be corrected by using a different emulsion or developer, or by changing the original. Another example is the failure to focus the corners of the image at the same time as the centre, which may indicate the need for a change of objective, or reduction of aperture or use of a field-flattening eyepiece. Changes of sharpness from one side to the other (or from top to bottom) can mean that the image is incorrectly centred, or that the plate is not lying squarely in the focal plane. Any such troubles must be corrected at the first hint, since it is useless to proceed with the tests while such errors remain uncorrected.

Inspection of Results

However perfect may be the apparatus and emulsion used, much of the quality of the final result will still depend on the operator's skill. An important constituent of this skill is the ability to observe small differences in the appearance of each of a series of images, so that a reliable estimate can be made of the best conditions for the exposure. This ability can be analysed into three parts, namely:

Visual microscopy,
Visual memory,
Interpretation.

It is first necessary to be sufficiently familiar with the adjustment of a microscope to ensure that the images are viewed by " critical " illumination, so that the image seen is a clear representation of the microphotograph. Instructions for doing this are given in any textbook on microscopy. The objective and eyepiece used for viewing the image should be chosen so that the area of the image fills most of the visible field. Use of lower magnifications than this will make sufficiently critical observation difficult, but higher magnifications are sometimes desirable. An oil-immersion objective is useful for checking the depth of the image in the emulsion layer, but is not normally needed for checking the sharpness of any but the very smallest images.

A full realization of the significance of focusing or exposure tests depends on the inter-comparison of each of a series of images. Inter-comparison depends on the ability to retain a mental picture of the appearance of one or more images viewed previously, so that the quality of the image inspected at any moment can be related to others in the series. Comparisons of this type are fairly easy to make when a series of photographs is laid out on a table, but become more difficult when the adjustment of a microscope introduces a delay between the viewing of successive images. The very act of finding the next image tends to blur the mental impression. The acquisition of a visual memory is another faculty which only grows with practice, but it can be assisted by making notes about the appearance of each image. One should also not attempt to visualize the appearance of the whole of the image, but rather concentrate attention on that part whose reproduction is likely to prove most critical.

The interpretation of the results depends on knowledge and experience, and will be discussed in the next section. We should, however, first consider the condition of the emulsion layer when the images are inspected. The images can be viewed in the wet emulsion immediately after fixing, when a cover-glass should be laid on the emulsion surface to prevent condensation on the objective. In a swollen gelatin emulsion the image is likely to be expanded vertically some three to five times, so that only part of the image can be focused at one time when viewing with an objective having a focal length of ½ in. (12 mm.) or less. The image may thus seem less dense than it will appear after drying down, and may also seem less sharp as a result of lateral distortion. For these reasons inspection of the wet image is only recommended when images are made with low degrees of reduction, or for very rough or preliminary tests.

In most cases it is preferable to dry the test plates before viewing. Since the images need not be very stable for this purpose, all the processing operations subsequent to development can be

shortened. Concentrated-Lippmann plates need only be fixed for two minutes, washed for two minutes with a stream of water falling directly on the emulsion from a tap, and dried with an electric hair-dryer (or in the hot air rising from an electric fire or gas ring) after rinsing in two parts of industrial spirit and one part of water. Wet-collodion plates can be dried even more rapidly, as the water content of the layer is so low during processing.

The assessment of test plates is also assisted by marking the images before viewing: a small bold ink circle round each of the images makes them easier to find. It is also helpful to mark the exposure or focus setting for each image at the same time.

Interpretation of Exposure and Focusing Tests

When viewing exposure or focusing tests it is important to keep the interaction between exposure and focus constantly in mind. It should, for instance, be remembered that inadequate density can just as well be due to incorrect focus as to insufficient exposure. Interpretation of these tests is also assisted by the ability to detect various other signs. Thus the finest lines are most sensitive to any change in conditions, while the degree of rounding observed at the intersection of two lines is a good indication of the quality of reproduction obtained. Consideration of the way in which the image quality changes through a series of test images can prove valuable, since there should be a steady modification of the image quality as the exposure or focus is altered. Thus with a series of increasing exposures the images should show a regular increase in the solidity of the lines. Any sign of irregularity in the series may mean that some additional factor, such as poor registration of the plate or vibration, may be affecting the images. It would be rash to continue with the series of test exposures until the trouble has been located and rectified. A focusing test should show a smooth and progressive improvement of sharpness up to the point of correct focus, followed by a smooth and progressive deterioration. Any lack of such a steady progression may indicate that random errors of focus are occurring. In this case an attempt to reset the focus to a desired position after inspection of the test is likely to prove unsuccessful. Such faults can be obscure and difficult to trace, but bitter experience has shown that it is a waste of time to continue until they have been corrected.

Valuable additional information can be obtained from a photographic-focusing test by studying the appearance of the out-of-focus images. If the objective produces the usual saucer-shaped field (*Figure* 27) the corners of the image will be the first parts to become sharp as the objective is moved away from the emulsion. The area of the sharp zone should then increase as the objective is moved still further, and the corners of the field may ultimately start to become unsharp while the centre is still sharp. Appreciation of this sequence of changes enables the direction of a necessary change of focus to be deduced from the appearance of a single image. Confirmatory evidence can be obtained by using an oil-immersion objective to estimate the depth of different parts of the image in the emulsion layer. Another useful indication obtained from partly sharp images is derived from the distribution of the unsharp areas about the centre of the image. If this distribution is symmetrical it indicates that the negative is correctly centred on the axis of the objective and the apparatus is truly square.

Maintaining a Satisfactory Image

When conditions giving a satisfactory image have been established, the process must be operated so that consistently good results are obtained. The main difficulties in maintaining a satisfactory image are often caused by the fact that the microphotographer is likely to be working close to the limits of performance of the emulsion and objective. To work close to these limits is an excellent exercise for developing technique, but does not favour the production of satisfactory images. It is better to use conditions which permit slight variations of focus, or exposure, or development to occur without spoiling the image.

Working tolerances can, in fact, be obtained in two ways. The first is to work well within the limits of performance of the emulsion and objective. The resolution of the system should, if possible, be capable of reproducing lines considerably finer than any shown by the required images. The whole of the image should also be comfortably contained within the central (and therefore near enough) flat field of the objective. A working tolerance gained from the depth of focus of the objective may otherwise be lost if the focus has to be adjusted so that the centre of the image is at the back and the edges of the image are at the front of the zone giving satisfactory sharpness. It is interesting to note that particular mention of the importance of such working tolerances is made in the report on the Möller graticule factory, and no little of the success of their production was ascribed to such precautions.$^{(2)}$

The second way of obtaining a working tolerance is concerned with the correct placing of the conditions within the permissible range. To do this the exposure and focusing tests should be performed so that they show not only the best conditions, but also the range on each side of the optimum giving tolerable image quality. In some cases it is then sufficient to choose working conditions in the middle of the range. In others, however, it may happen that the deterioration on one side of the optimum may be more rapid than on the other. While increasing exposure, for example, may thicken the lines, some slight thickening of the finest lines by over-exposure may be preferable to their complete disappearance by an equivalent degree of under-exposure. Similarly the loss of resolution resulting from placing an image rather deeper in the emulsion will be much less than if the focal plane is placed in front of the emulsion. In the former case a correctly-focused image is formed in a lower layer of the emulsion, while in the latter only an out-of-focus image is formed at all. It thus follows that estimations of the permissible range are best made *directly* from the images in series of test exposures.

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CHAPTER 10

Anomalous Image Formation

THE EXTREME RESOLUTION of microphotographic emulsions means that they can record the fine structure of an image : a property which may sometimes lead to quite surprising results. Under conditions which might merely give an unresolved image on emulsions with lower resolution and higher speed, a microphotographic emulsion can sometimes show an image which is more like a caricature than a straightforward reproduction of the original. Such anomalous images are worth studying in some detail, since they constitute defects whose explanation usually indicates a remedy.(1) They also provide valuable clues to the complex processes associated with image formation.

Properties of the Emulsion, and of Negatives Produced from it

The observations described in this chapter were all made on " Kodak " Maximum Resolution emulsion, and the following properties of this material are significant for their interpretation. The concentrated-Lippmann emulsion is coated to give a dried-down layer 5–7 μ thick, which scatters very little blue-green light and is substantially transparent to it. This has been demonstrated by exposing an M.R. plate behind another layer of the same emulsion, when the covered emulsion was found to have retained about half its speed. Thus the light intensity reaching the lowest emulsion layer of the coated plate is about 50 per cent. of that in the emulsion surface. The emulsion gives a high contrast (gamma values of 5 or more are obtained in D.178, Appendix I, A), and the spectral sensitivity shows a strong dye-sensitized band with a peak at 5,300 Å. (*Figure* 17).

The surface of developed " line " negatives on this material shows a definite " relief ", and a cross section demonstrates that the additional volume of the developed-silver deposit causes the blackened areas to be thicker than the unblackened (*Figure* 57).

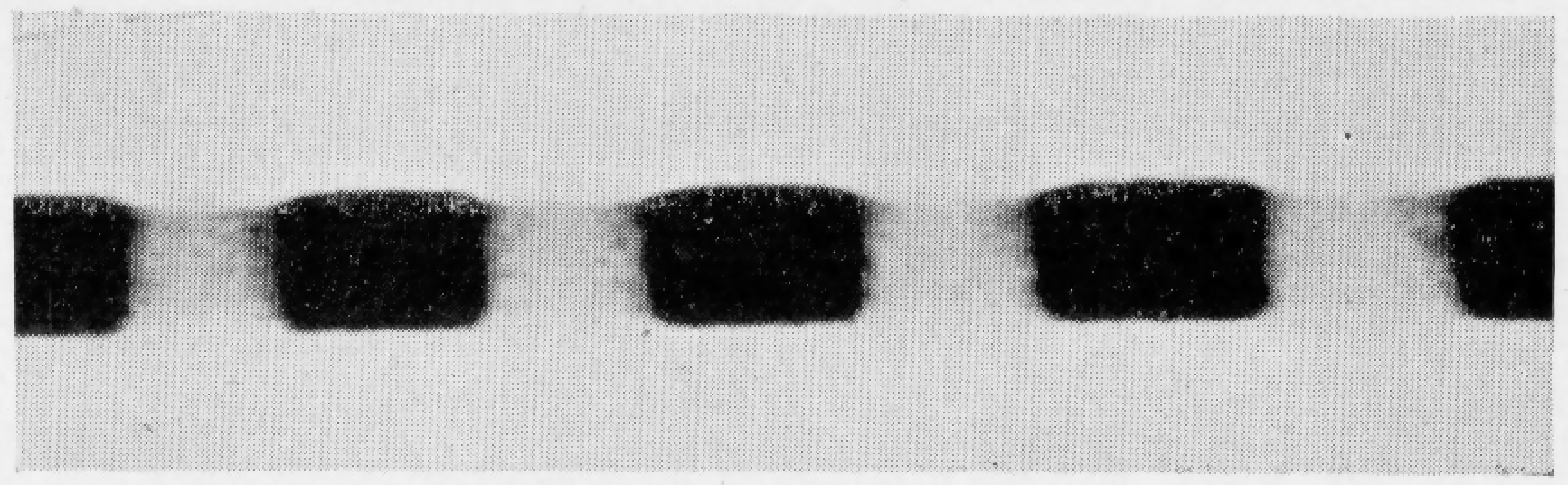
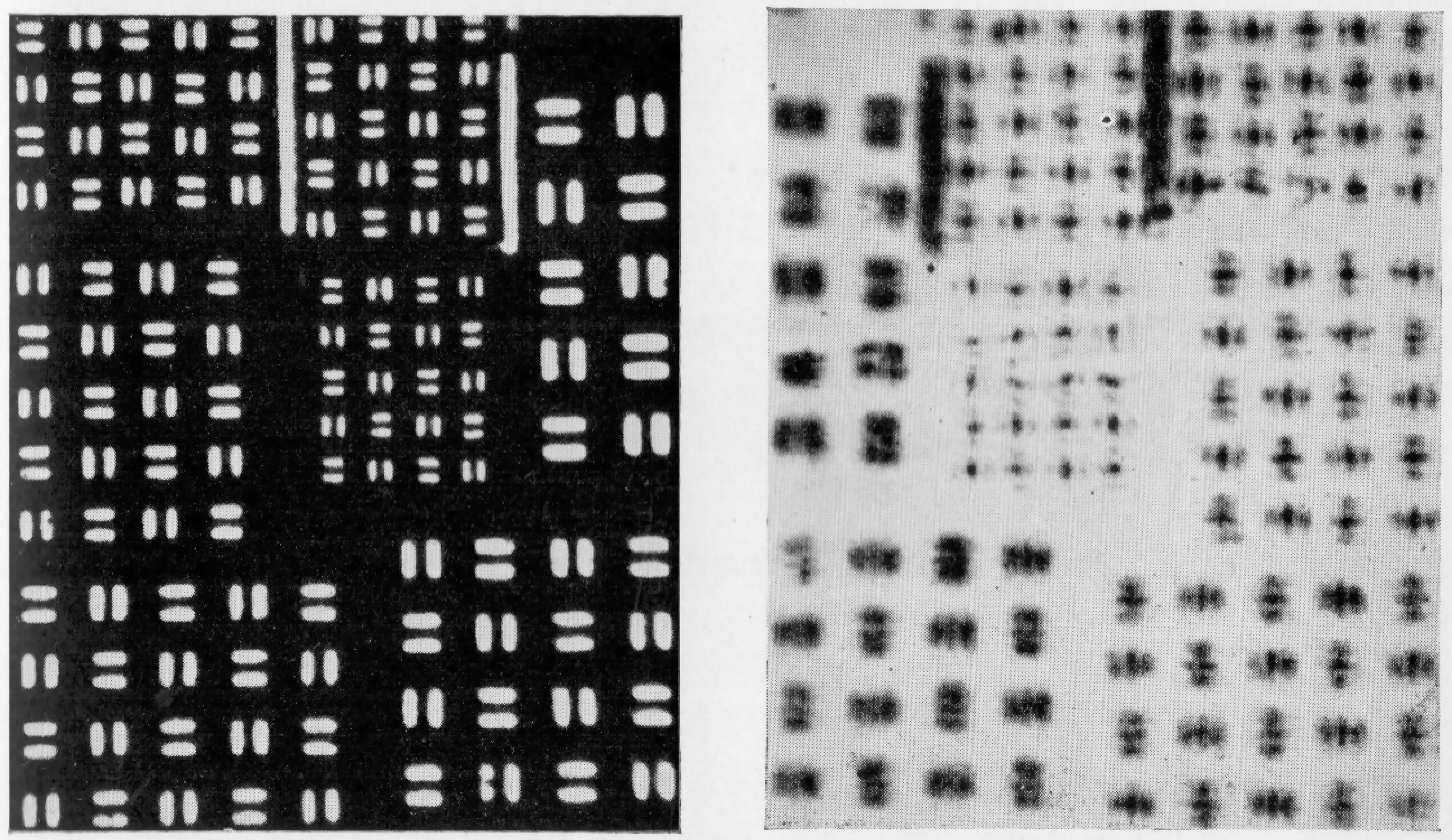


FIG. 57. *Lenticular Surface of Processed Image.*

Section of dry Maximum Resolution emulsion containing a graticule image (×950). Note how the volume of the developed silver increases the thickness of the layer in the blackened parts.

Photomicrograph by courtesy of Miss J. Tabor. Kodak Research Laboratories, Harrow.



(*a*) (*b*)

FIG. 58. *Spurious Resolution in Contact Printing.*

(*a*) Test-chart image (×460). The groups shown correspond to resolution figures of 400, 360, 330, 295, 270, 245 and 220 lines/mm.

(*b*) Contact print on Maximum Resolution plate made after test-chart surface had been scratched in use. Some groups are reproduced by *three* lines instead of two.

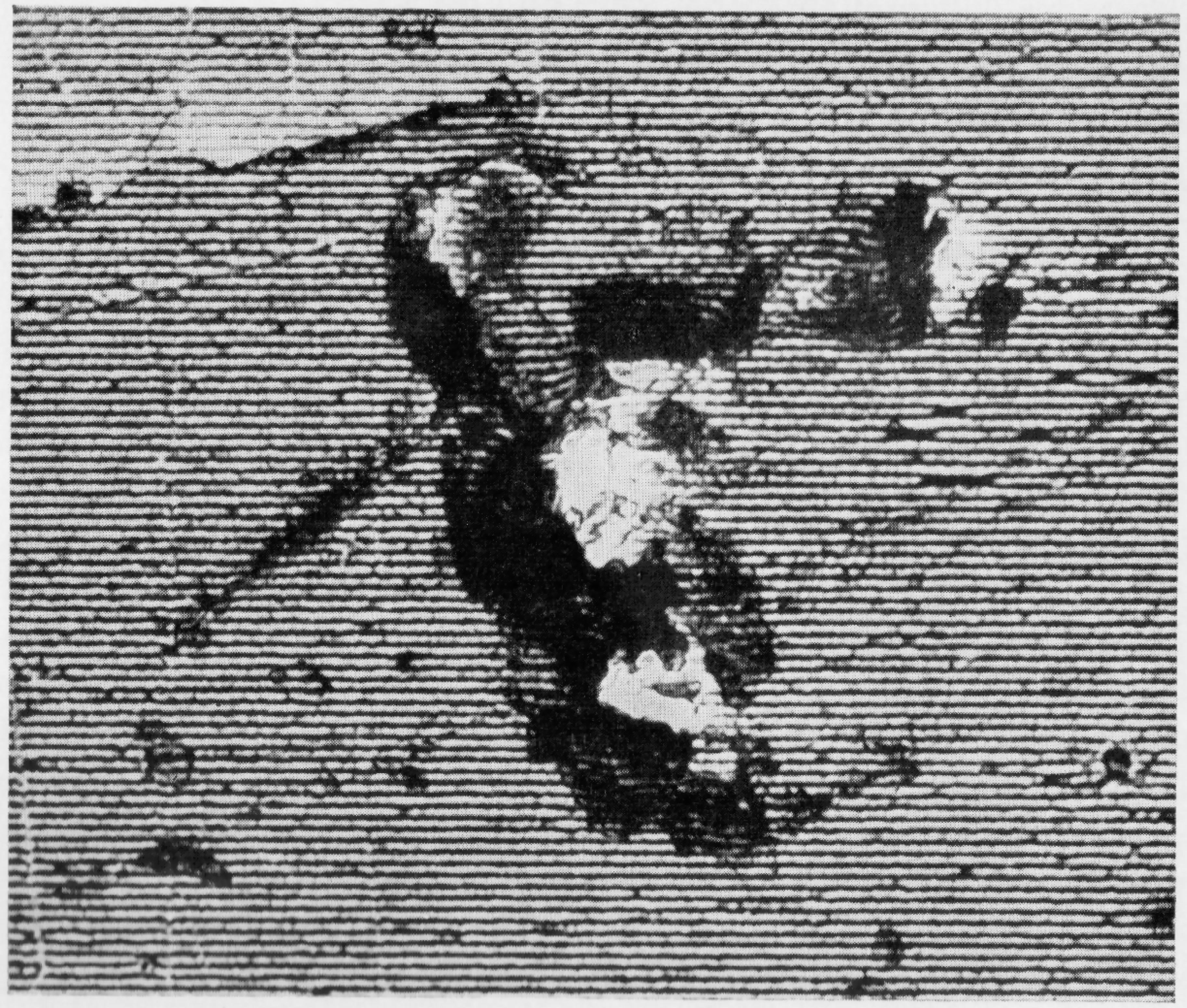


FIG. 59. *Scratched Surface of Diffraction-grating Copy used as Contact Test Chart.*

Photomicrograph (×580) of image on Maximum Resolution plate. The way in which the emulsion has piled up in the scratch can be seen from the distortion of the lines of the grating.

[Facing p. 183.

The emulsion surface, particularly in the transparent images of the lines, thus has a definitely lenticular configuration.

Multiplication of Images when Contact Printing

Resolution test-chart images were reduced on M.R. plates with a 4-mm. Beck achromatic objective, and the reduced images showed satisfactory resolution of the finest group corresponding to 400 lines/mm. (*Figure* 58*a*). The performance of the test chart was examined by contact printing in a pressure frame on M.R. plates, and it was found that satisfactorily resolved positive images were at first produced even from the finest group. After the test charts had been used for some time, however, it was found that really sharp images could no longer be produced. Careful examination of these later tests showed that some of the elements of the image were now represented by three lines instead of two (*Figure* 58*b*). As this result had been obtained while contact printing, some disturbance of the light must have occurred in the short distance between the test chart and the recording emulsion. Similar results were obtained on a number of occasions and the following factors were found to influence the appearance of the images:

(i) The emulsion surface of the test chart had become badly scratched during use, and crumpled heaps of gelatin had piled up at the ends of many of the scratches (*Figure* 59). These must have prevented effective contact, in spite of the pressure applied by the frame.

(ii) For any one test, there was one size of image showing the three-line effect most clearly. Groups of images ranging in size by 20 per cent. on each side showed the effect less clearly.

(iii) The size of the images showing the effect increased with decreasing pressure, and hence presumably with increased separation between the test chart and recording emulsion surface.

(iv) With any given pressure the size of test chart showing the effect most clearly was reduced by from 20 per cent. to 40 per cent. by inserting xylene (refractive index 1·5) between the test chart and the emulsion under test. This change was accompanied by an increase in sharpness of the largest images.

(v) Exposure with parallel light gave a result only slightly different from that produced by exposure to a Photoflood lamp at 2 ft., but illumination with a very wide cone of light caused gross deterioration of sharpness and the three-line effect could no longer be seen.

Now it is clear that even with parallel light there is a serious difference between the appearance of the image and the geometrical shadow of the test chart. At least two phenomena may be contributing to this effect. The width of the slits forming the test-chart image is sufficiently small for diffraction to be observed at a small distance. This would cause each slit to appear as a dark central image, with a secondary, less dense band on each side. A third image between the central images of each pair of slits could then be formed by overlapping of these secondary bands. The lenticular emulsion surface of the test-chart image probably also plays a part, with each slit effectively acting as a diverging cylindrical lens. Refraction would thus cause part of the transmitted light to be diverted sideways, and mutual reinforcement of the diverted light from each of a pair of slits could cause a third image to be formed between them. The available evidence was insufficient to distinguish between these causes, and it seems probable that each was having a contributory effect. The primary cause was, in any case, the scratching of the surface of the test chart. The remedy was to use a new test-chart image, and take the utmost care to remove particles of dust before the emulsion under test was clamped against it.

Interference Effects observed with Contact Printing

The following observations were made during an experiment on the production of small graticules by contact printing. A $\frac{2}{3}$-in. (16-mm.) Watson achromatic objective was used to make a negative image of a scale with 28 μ divisions and lines 3 μ wide (*Figure* 60*a*). The field covered was small, and the negatives consisted of blackened circles with a total diameter of only $\frac{1}{16}$ in. (1·5 mm.) in the centre of which were the graticule images. Contact prints from these images were likely to be spoiled by light spreading in from the rest of the illuminated plate. A photographic " opaque " medium was therefore painted round the negative, to prevent the background

from printing up.* Contact prints made from a negative in this condition were very unsharp, and showed an extraordinary banded and spiky pattern (*Figure* 60*b*). A prominent feature was a pointed cross formed at the intersection of the lines, and inclined at 45° to the original lines of the negative. This effect seemed to be primarily caused by poor contact resulting from the thickness of the layer of opaque medium. Measurements with a micrometer showed that the dried-down thickness could be from 0·0004 to 0·0012 in. (10–30 μ). Contact prints made under the same conditions from a fresh negative showed reasonably sharp images. Prints from the negative with opaque medium on its surface were strikingly improved by filling the air space between the two gelatin surfaces with xylene (*Figure* 60*c*).

The experiments so far described were all directed at preventing the effect. The faulty images certainly had a strange appearance, but the abnormality was not sufficiently well defined to permit a detailed analysis. Some additional experiments were therefore made with the aim of increasing the clarity of the pattern. The air space was increased to about 0·003 in. (70 μ) by placing a " Cellophane " mask, cut away in front of the images themselves, between the negative and the M.R. plate. Prints made with parallel light from a " Pointolite " lamp focused with a condenser then showed the pattern in an exaggerated form. A print exposed for seven seconds showed virtually only the pointed cross, while ten seconds' exposure showed that the horizontal line was replaced by a series of intersecting arcs (*Figure* 60*d*). The pattern was further sharpened by exposing to a high-pressure mercury-vapour lamp through a " Wratten " No. 15 filter, so that monochromatic light of wavelength 5,460 Å. was almost entirely responsible for image formation. In addition to the features already observed, the pattern now showed sets of fine vertical fringes both in the images of the vertical lines and filling the spaces between them (*Figure* 60*e*). The combined width of a dark and light band was about 0·00006 in. (1·6 μ), corresponding to a line frequency of 600 lines/mm.

Now poor contact was obviously the primary cause of these effects, but a detailed explanation would have to account for both the low proportion of transmitted light found in the geometrical projection of the test chart, and the elaborate patterns formed. The remarkable improvement produced by xylene indicates that refraction at the lenticular surface of the negative probably resulted in the diversion of much of the light. The reality of this lenticular surface was demonstrated by making a cellulose-acetate casting of the emulsion surface. When stripped, this showed every line of the image (*Figure* 60*f*).

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* See Chapter 11 (page 217), for a description of other methods for blackening the background.

The spiky pattern shown by *Figure* 60 (*d* and *e*) vividly resembles a system of intersecting ripples, and the whole appearance of these images suggested that interference effects were occurring. If we consider the basic pattern of the negative (*Figure* 61), it seems that interference effects might occur in the following ways :

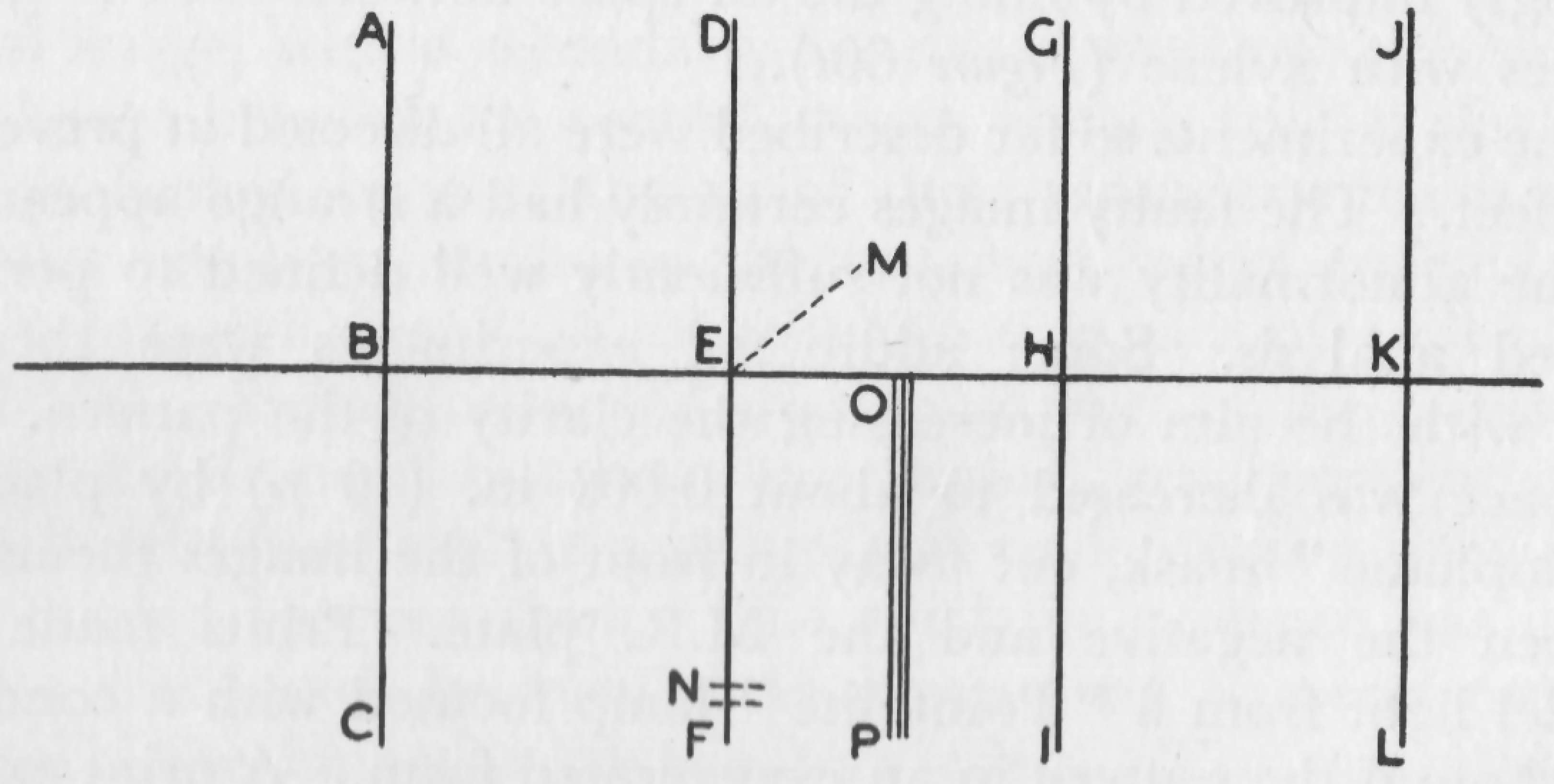
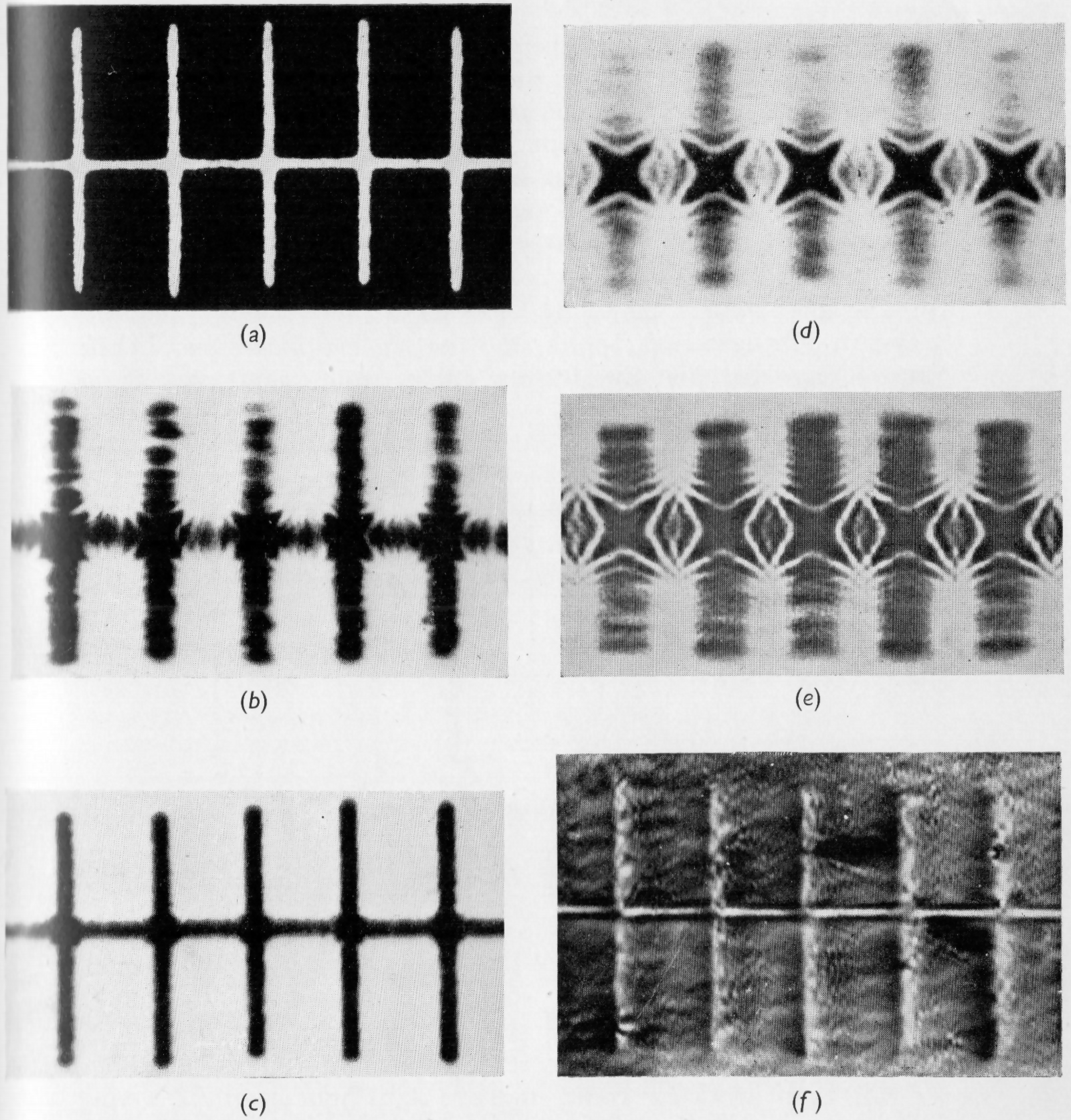


Fig. 61. *Modes of Interference.*

(i) Light transmitted by the horizontal line *EH* could interfere with light from vertical lines such as *ED*. Reinforcement along a 45° line (*EM*) would account for the pointed cross.
(ii) Light from *E* might interfere with light from *B* and *H*, giving the banded structure shown at *N*.
(iii) Light from *EF* could interfere with light from *HI*, giving vertical lines at *OP*. At the same time light from *BC* and *HI* could interfere with the light from *EF* to give a banded structure even inside the geometrical images of *EF*.

Interference effects not only account for the main qualitative features of these images but, from the dimensions of the system, should enable us to calculate the wavelength of the light used.



(*a*) Negative graticule image (×460).
(*b*) Contact print on Maximum Resolution plate from negative spotted with opaque medium.
(*c*) Print with space between negative and emulsion filled with xylene.
(*d*) Print by parallel light and air space increased to 70 μ (about 0·003 in.).
(*e*) As (*d*), but print made by monochromatic light. Note complex interference fringes.
(*f*) Photomicrograph of cast from negative surface.

Fig. 60. *Image contorted by Interference.*

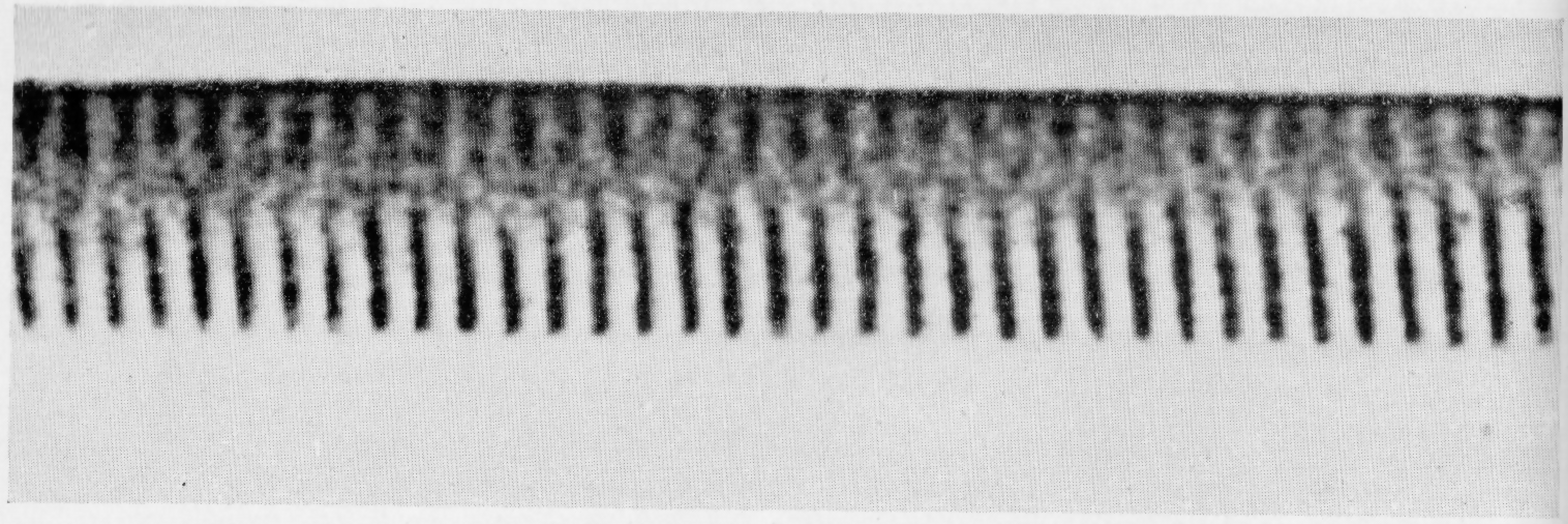


FIG. 62. *Emulsion bearing Image in its Lower Half.*

Transverse section (× 1800) of dry emulsion layer showing sharp image in lower half and spurious resolution in upper layers. Note how the lines of the spurious image are staggered with respect to those of the genuine image.

Photomicrograph by courtesy of Mr. J. A. Carter. Kodak Research Laboratories, Harrow.

[*Facing p. 187.*

It was assumed that each vertical fringe represented a locus along which light from adjacent vertical lines of the negative is in phase. On this assumption, and with an estimated emulsion-to-negative separation of 70 μ, the fringe separation of 1·6 μ was shown to correspond to a wavelength of 6,000 Å. The fact that this calculation gave a wavelength figure close to the actual value of 5,460 Å. confirms the hypothesis that the patterns are caused by interference.

Spurious Resolution in Projection Printing

The action of " optical sectioning " (Chapter 9) was demonstrated by deliberately making images in the lower half of a specially thick (11 μ) experimental coating of M.R. emulsion on film. The objective used was an achromat of N.A. 0·4, and this projected a system of parallel lines with a frequency of 12,500 lines/in. (500 lines/mm.). Inspection of the swollen processed emulsion was used to set the focus so that the image was restricted to the lower part of the emulsion layer. When the thinnest possible transverse sections were cut, it was at first found that the images had insufficient density. The exposure was therefore increased to a level at which the final image in the dried-down emulsion appeared definitely over-exposed when observed by transmitted light. Dry sections of the processed layer now showed sharp images of dense narrow lines confined to the lower half of the emulsion layer (*Figure* 62). The section also showed that the upper limit of the sharply-focused zone sank through the emulsion layer from right to left ; probably as a result of field-curvature of the objective.

Another notable feature of this section was that the top part of the emulsion layer contained poorly-resolved images consisting of slightly wedge-shaped bands " staggered " with respect to the sharp images in the lower half of the emulsion. It seemed probable that these spurious images were caused by the overlapping of the cones of rays converging to form images of neighbouring lines. The probability of this hypothesis was examined by making a scale drawing in which a series of cones from an objective of N.A. 0·4 were drawn so that they produced sharp images 2 μ apart at a depth of 7 μ below the surface of an emulsion of refractive index 1·5. The result gave a pattern in which the overlapping zones corresponded reasonably well to the spurious images with respect to position, size and shape (*Figure* 63). The spacing of the rays in the overlapping zones suggests that the light intensity should be low compared with that at the correct focus, but this will depend on the light distribution in the image. If spherical aberration gives an image consisting of a bright ring with a dark centre just inside the point of focus, a high proportion of the light will be concentrated in the outer part of the cone and hence tend to increase the intensity in the overlapping zones.

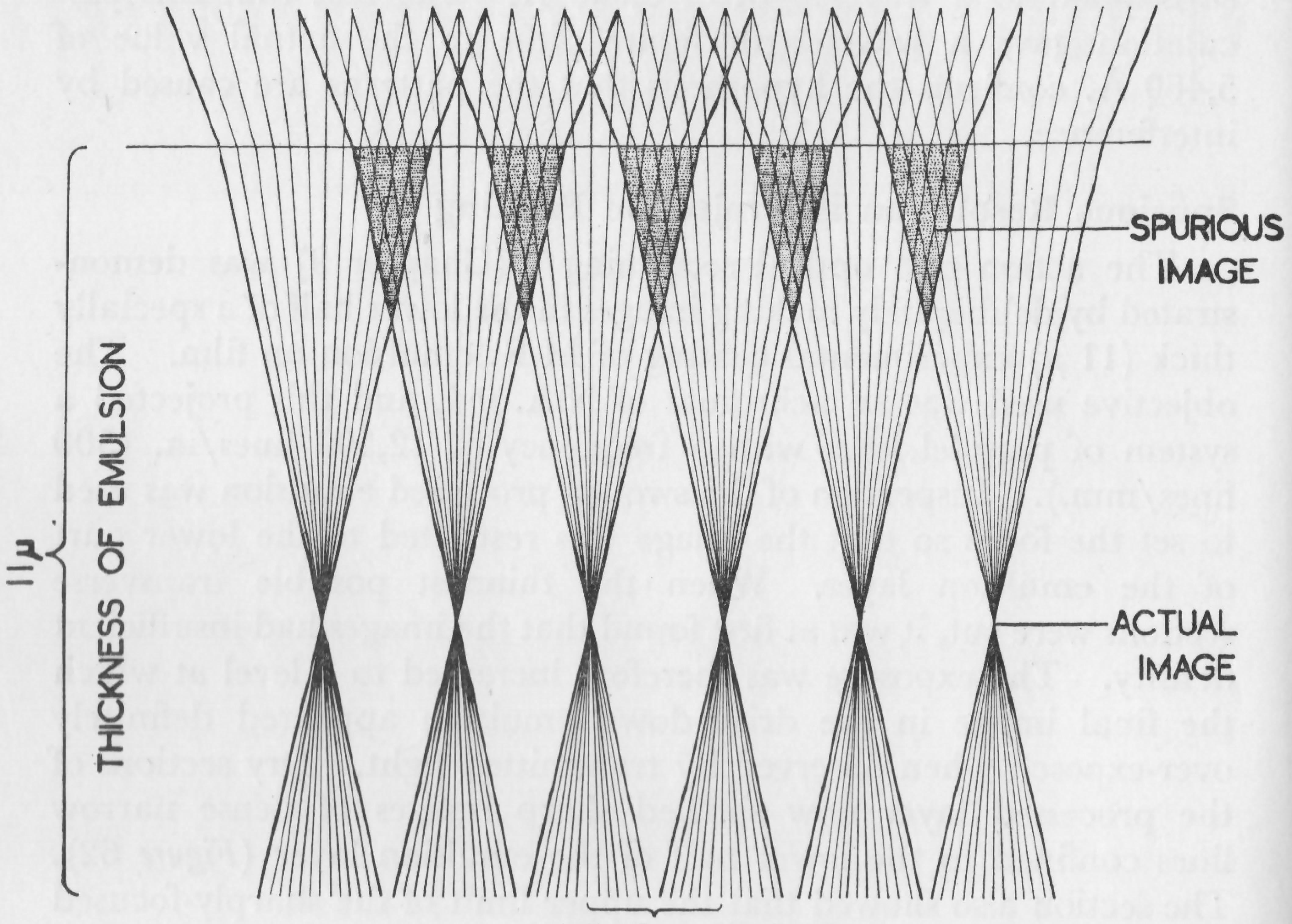


Fig. 63. *Formation of Spurious Image.*

The Significance of Anomalous Images

Results described in this chapter show that even such apparently simple operations as contact printing are beset with various difficulties when very fine lines have to be produced. The use of pressure frames, the application of spotting media only to the back of the negative, care in handling to avoid even minute scratches, and introducing a liquid such as xylene between the negative and the recording emulsion surface are precautions which lessen the difficulty.

The extreme sharpness of the edge of a fine line in a microphotographic emulsion provides ideal conditions for observing the consequences of the lenticular surface of processed emulsion layers. Such effects may, however, also occur on " process " plates of higher speed and lower resolution. When processed by conventional methods, images on such emulsions show a more or less diffuse edge ; but autocatalytic development of the " lith-type " emulsions, or " cutting " and intensifying result in a much sharper edge. The high silver-halide content of these emulsions relative to microphotographic materials, and the increase in the mass of the image produced by intensification will also increase the ratio of the thickness of blackened areas to that of unblackened areas. These considerations suggest that effects due to a lenticular emulsion surface may frequently influence the contact printing of photomechanical screen or line negatives. They could, for instance, be responsible for the observation that the image of a line positive usually appears smaller than the line negative from which it has been made. As a result of this effect, a transparent margin can usually be seen when the dry positive is held in register with the negative.

Spurious resolution occurring during image formation by lenses has been reported by several previous authors. Hamblin and Winser (2) observed such an effect when using a line grating for visual measurements of resolution. They stated that it is caused by the overlapping of blurred images of several lines of the grating. In the discussion of their paper it was said that such effects are well known to microscopists. Washer (3) observed the effect photographically in the resolution testing of photographic objectives and found that a fine pattern frequently appeared resolved in out-of-focus planes, when coarser patterns in the same image were not resolved. Selwyn (4) illustrated this phenomenon by photographing the reduced image of a resolution test chart, with the film placed in an out-of-focus plane. With decreasing line width the contrast of the image at first fell, until the lines of the test images could no longer be resolved. A further decrease of the line width, however, produced an increase of contrast, so that the images of still finer lines showed a line structure. The spuriously resolved lines were reversed with respect to tone reproduction, and had a dark band where the images should have been light. This is obviously equivalent to the " staggering " of the spurious images shown in *Figure* 62. Spurious resolution has also been fully investigated by Hotchkiss, Washer and Rosberry, who noted that this reversal of tones is a characteristic feature.(5)

Now all these previous observations were made by techniques giving substantially two-dimensional images. In general, a correctly focused image giving normal resolution would be seen or photographed at one focus setting, and an out-of-focus image showing spurious resolution would be recorded at a different setting. *Figure* 62, however, shows both types of result recorded at a single focus setting within the thickness of a single emulsion layer. Such a microphotograph is, in fact, a three-dimensional photograph in the literal sense of the words, and other possible applications of this type of result are discussed in Chapter 13.

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CHAPTER 11

Graticules (Reticles)

THE OPTICAL PARTS of measuring instruments have often to be provided with fine reference marks to assist in determining the size, position, shape or distance of the object under observation ; and these have come to be known as *graticules* (*reticles* in the United States of America). These names have been used to describe a variety of objects such as stage micrometers, eyepiece micrometers, scales for the eyepieces of military instruments, thread-profile gauges and non-parallax scales, so that a precise definition of their scope is hardly possible. The images of many graticules are relatively large, but even these frequently contain lines of such a quality that only inspection at a considerable magnification will give the full precision which the scale can offer.

The study of the design of graticules and their methods of use and production is a substantial and technologically important subject, which has so far received only scant attention in books dealing with optical instruments. It is, in fact, a subject so wide that the material in this chapter could be expanded to fill a volume by itself ; the present treatment should therefore only be regarded as an introduction.

History

The first and simplest forms of graticule were made by stretching wires or hairs or threads from a spider's web across a frame placed in the optical plane of a telescope or microscope. These methods are still used for making " cross-wires " for the " sighting " of telescopes. Even finer lines were obtained by the use of Wollaston wire, which is made by drawing out a silver wire with a platinum core and then dissolving away the silver to leave a platinum wire which may have a diameter as fine as 0·00005 in. (about 1 μ). More elaborate patterns and divided scales have been made by mechanically engraving lines on metal or glass, or by scribing through a chemically-resistant layer and etching the base chemically. Very beautiful results can be obtained by these techniques, but such scales can only be produced with elaborate and expansive pantographs or dividing engines. Any lack of regularity in the engine can lead to variation from one scale to the next, and only the most refined mechanisms can be used for this purpose. Moreover, the ruling of each line on each scale is a separate operation, and the cost of the scales therefore rises rapidly with the number of lines.

The art of making fine rulings had already reached an advanced stage before photographic methods were introduced. Thus, in 1851 at the exhibition at the Crystal Palace in London, M. Nobert of Barth in Prussia showed groups of ruled lines used for testing the resolution of microscope objectives. A glass slide contained ten groups of lines of increasing fineness ranging from 11,265 down to 49,910 lines to the inch (approximately 450 to 2,000 lines/mm.). Photographic techniques available in 1956 would only permit a comparable fineness to be obtained over a very small area. It was also in 1851 that Scott Archer made the first detailed description of his wet-collodion process, and this was shortly afterwards used by Dancer to produce the first successful microphotographs. In addition to continuous-tone images, Dancer also made minute scales which were discussed in 1857 by Brewster (1) in an article showing a clear insight into the possibilities of these images :

> Mr. Dancer of Manchester has succeeded in making photographic portraits on collodion so small that 10,000 can be placed in a square inch. The film of collodion is so thin and transparent that it is invisible and allows objects to be seen through it as distinctly as if it were the thinnest glass. If a system of opaque or transparent lines, therefore, is impressed photographically, when reduced to the minutest size from a system of large and sharply defined lines, we shall have the most perfect micrometrical scale that can be conceived, the portion of the collodion that contains no silver being as transparent as if the dark spaces were solid wires or metallic plates placed in the focus of the eye glass.

This is a very clear statement of the idea of using photographic methods for making graticules. It is interesting to note that the author assumed that there would be no difficulty in producing a perfectly clean background to the scales, whereas this is one of the most troublesome difficulties encountered to-day. This article shows that Dancer was probably the first to have produced satisfactory graticule images, even if he did not himself originate the idea of making graticules photographically.

In the same article Brewster discussed the *reticle* or *reticulum* designed by the astronomer Cassini. This consisted of four wires crossing in the centre of the field, which thus obscured the critical point at which the actual observations had to be made. He commented :

> In the photographic form of this micrometer, this evil is completely removed by leaving the point of intersection of the lines transparent, so as to form a minute circular space.

This is probably one of the first published statements pointing out how photographic methods could overcome the limitations of the older type of graticule.

Later he discussed eyepiece micrometers :

> An annular micrometer with one or more rings of different diameters and breadths may be formed photographically. By reducing large rings formed by black ink and fine compasses a more correct circular edge may be obtained than by the turning lathe. Luminous rings may be formed of such extreme narrowness that the star will, as it were, leap through the interval in passing across the field of the telescope.

Applications to microscopy are also mentioned in another article by the same author (2) :

> Collodion in thin layers is as transparent as glass, even under high powers, and the lines are absolutely black and smooth at the edge. Circular spots of minutest size can be formed in a similar manner, so as to enable us to compare them with similar microscopic objects as discs of blood. Small angular spaces with divisions along the line which contains the angle may be advantageously used in microscopical micrometry.

Other workers soon became active in this field. Thus in England, W. Hodgson (1856) (3) and T. Maltwood (1858) (4) made stage micrometer images, as did Clarence Morfit of the Assay Office of the United States of America in 1860.(5) Morfit divided one-twentieth of an inch into a hundred parts, thus making a scale only slightly larger than the standard millimetre micrometer (approximately one twenty-fifth of an inch) used to-day. T. Maltwood also produced larger scales used as " finders ". A microscope slide was made with a square inch (25 mm. square) divided into 2,500 squares with sides of $\frac{1}{50}$ of an inch (0·5 mm.), and each small square was numbered. When a search of a slide of a biological specimen had revealed an interesting detail, its position was ascertained by substituting the " finder " slide in precisely the same position as the specimen. The record of this position could later be used to find the detail with a minimum of delay.

The pioneering experiments of these craftsmen seem to have been appreciated only by the enlightened few, and these developments aroused but little commercial interest in Great Britain. Some decades later, German instrument manufacturers started to apply photographic methods to the making of graticules. A review of stage micrometers made by M. D. Ewell in 1908 described the photographic scales made by the German firm of J. D. Möller.(6) He found that their photographic scales were as accurate as commercial examples of ruled scales. Details of the method used by Möller, which were described later, showed that he employed the wet-collodion process in much the same way that Dancer must have used it.(7)

The author has been unable to ascertain whether any commercial production of photographic graticules had occurred in Great Britain prior to 1914, but there is no doubt that a small number of German and Austrian manufacturers had by that time virtually established a world monopoly in graticules. This resulted in a shortage of the types required for gun-sights, which seriously embarrassed the artillery used by the Allies in 1915. Rheinberg described how he and other workers were stimulated by Professor F. J. Cheshire to work out techniques for graticule production as a problem of national emergency.(8) The earlier work done in this country seems to have been so completely forgotten that the original name of *reticle* was quite overlooked. The word *graticule* was coined during this period and seems to be too widely used to be readily displaced. An Englishman cannot help feeling ashamed that the historically more correct word *reticle* is still used in the United States of America !

The early history of the graticule industry in Great Britain bears a striking resemblance to that of synthetic dyestuffs. The first synthesis was carried out in England by W. Perkin (later Sir William) while still a schoolboy, but by 1914 the Germans had such a world monopoly that the Allies were seriously troubled to obtain sufficient dye for military uniforms. It has been suggested that this type of situation was caused by the past reluctance of British industrialists to support any scientific endeavour which was not an immediately paying proposition.(8) The advantage resulting

from Great Britain's lead in the Industrial Revolution may have blinded them to the need for continuous technical improvement in a period when other countries were extensively applying the results of research. A determination to avoid repetition of these past mistakes was one of the motives for the foundation of the Department of Scientific and Industrial Research by an Order in Council on July 28th, 1915.

During the 1914 war, J. Rheinberg and one or two other groups established the large-scale production of graticules for military instruments, but the peace-time requirements for such products is comparatively small. After the First World War some production-units were dispersed through lack of work, and others (such as the firm of Rheinberg—now Graticules Ltd.) continued production on a reduced scale, using secret processes which have never been published. The need for graticules for scientific instruments was, however, still apparent, and in 1928 the British Scientific Instruments Research Association started an investigation into methods of production as the result of requests from member firms. The author is indebted to Dr. E. Bovey (head of their Photographic and Optical Processes Department) for the following account of their work :

> At first the objectives were somewhat limited, and it was thought that a term of about two years would complete the work. As the research progressed, it became obvious that the scope of the work would have to be extended to cover an increasingly wide range of graticule types. Five basic processes were worked out and are known as :
>
> (1) Colloidal silver.
> (2) Silver line.
> (3) Photo-etching.
> (4) Lead sulphide.
> (5) Ruling and etching.
>
> The Association introduced these processes to member firms, and they were used alone or in combination, according to the particular need.
>
> With the onset of the Second World War, graticule requirements reached an unprecedented figure and B.S.I.R.A. was occupied in training operatives from member firms, improving existing processes and designing new ones, and disseminating information on graticule production among representatives of the Commonwealth and United States of America. As a result, their processes have had world-wide application. They materially assisted in the war effort of the optical industries of Australia, India, South Africa and the United States of America.
>
> During the past decade, changes in graticule design have gone hand in hand with demands for higher accuracy, both in overall dimensions and

in the width of the constituent lines of the pattern. Such requirements have been particularly noticeable in the specification for divided circles used in optical theodolites. These instruments are now capable of measuring angles to an accuracy of 1 second of arc. The demands on the accuracy of the graticule process can be readily appreciated. B.S.I.R.A. processes have been successfully employed in the manufacture of these highly accurate divided circles. Although most graticules are made on a glass support, the various processes have been modified for particular requirements so that the images may be produced on other materials such as metal and plastics. Patterns have also been applied to convex and concave surfaces. More recently the application of metal vacuum-evaporation and sputtering processes has widened the scope of methods employed at B.S.I.R.A. It is now possible to produce permanent graticule patterns of platinum, rhodium, chromium and aluminium on glass.

Other groups, such as the London School of Photo-Engraving at Bolt Court, assisted this work during the Second World War.(9) A large number of graticules were made under the leadership of Dr. A. J. Bull, who has given a graphic account of war-time production of graticules in a city subjected to aerial bombardment. Valuable contributions were also made by commercial firms, such as the introduction of the 548 and 649 G.H. plates by the Eastman Kodak Co. in the United States, and the Maximum Resolution plate by Kodak Ltd. in England (Chapter 3). The Kodak Research Laboratories in Rochester and Harrow also developed and operated processes for making graticules. One of their processes (described later) produced small metal parts with delicate and intricate shapes, which have potential uses outside the normal field of graticules. An interesting description of the production of graticules during this period has also been given by Geiser.(10)

In 1919, Rheinberg(8) discussed possible future trends in the use of graticules, and suggested that, if suitable scales were available, it would permit optical-instrument designers to improve existing apparatus or develop completely new types. In particular he considered that the principle of arranging the scale, so that a measurement could be made at the same time as the object is observed, was well worth further study. This method of reading is, of course, quicker and more convenient than the time-honoured method of setting " cross-wires " on the object and then taking the measurement from a scale, which may have to be observed with a separate reading microscope.

Rheinberg's observations were truly prophetic, and instruments embodying the type of improvement he forecast have now been constructed. Thus in the 30th Exhibition of the Physical Society,(11) a number of instruments were displayed containing accurate glass scales used in conjunction with optical micrometers. These scales gave freedom from wear and corrosion, improved accuracy and stability, and enabled the whole size and weight of the instrument to be reduced. The last-named advantage is particularly important for surveying instruments, which demand extreme accuracy and have to be transported over all types of country. The 32nd Exhibition of the same society displayed a theodolite which contained circular glass scales with optical micrometers reading to one second of arc.(12) A new optical system permitted graduations at opposite ends of the diameter of the circle to be brought into coincidence to give an automatic mean, and the separate optical systems for reading the horizontal and vertical scales were brought to a single reading-telescope. The convenience of this arrangement for surveyors, particularly when working in bad weather, can readily be imagined.

Technical Problems of Graticule Production

Two main groups of technical problems can be discerned in the study of the application of extreme-resolution photography to scientific instruments. In the first place, many graticules are an essential and integral part of an optical instrument and may remain in the field of view for many hours. They can thus play a decisive part in determining the accuracy obtainable from the instrument and the fatigue or comfort experienced by the operator. A good case can, in fact, be made for the study of the use of graticules as a specialized branch of psychological optics in the same way that psychologists studied the interaction between complex machines or weapons and their users during the 1939–45 war.

Secondly, the production of graticules presents many problems, and in the past the difficulties have sometimes been increased by the way in which the work has been carried out. Some of these difficulties can be traced to the failure to realize that even photographic methods have their limitations. It has, for instance, been known for a potential user to commission a draughtsman with little previous experience to produce a design. The user has then approached the production unit in the expectation that the graticules will be produced in a short time, even though the design introduces insoluble production problems. Successful execution of such work clearly calls for the co-ordination of the needs of the instrument maker, the graticule producer and the final user of the instrument.

Factors affecting the Design of Graticules

It is convenient to group the factors which have to be considered in designing a graticule on the basis of our two types of technical problems :

Group 1. *Factors concerned with the visual performance of the graticule.*

(1) The nature of the pattern.
(2) The method of illumination of the scale.
(3) The dimensional accuracy of the scale.
(4) The degree of cleanliness required in the background.

Group 2. *Factors influencing the production and life of the graticule.*

(5) Nature and specification of support.
(6) Nature of material forming the pattern.
(7) Resistance of the scale to adverse handling.
(8) Special physical properties of the image.
(9) Influence of design on price and production.
(10) Suitability of photographic methods.

(1) *Nature of the Pattern*

Graticules are used for estimations of distance, or position, or shape, or size, or numbers, and analysis of the proposed observations into their essential components will usually indicate the general form the pattern should take. Optimum results are, however, only likely to be obtained if one also considers the way in which the eye functions while making the observations. Useful guidance on such problems can be obtained from experiments in applied psychology, in which the influence of line width or scale design on accuracy of reading have been studied.

Rheinberg [(8)] has pointed out that several details in the design of a graticule may influence its efficiency and the ease with which it can be used. The nature of the pattern should be designed with a view to :

(i) the ease with which the eye can find and concentrate on essential details ;

(ii) the avoidance of distracting details ;
(iii) the ease with which any feature in the object plane can be seen, inspected and identified, even when part of the pattern is superimposed on it.

He emphasized the importance of simplicity in the design and suggested that the ease with which extra matter can be inserted in photographic graticules may act as a temptation to load the pattern unnecessarily.

A number of suggestions have been made for obtaining the greatest accuracy when making coincidence observations. Thus, Martin discusses the arrangement of cross-wires for measuring microscopes.[(13)] When the cross-wires have to be set on a diffuse line, such as the line of a spectrum taken on a high-speed plate, arrangement (*a*) (*Figure* 64) is bad, as the line is obscured ; (*b*) is better but not good ; and (*c*) is very good. With arrangement (*c*), the separation needs to be adjusted to the line width, so that the slightest movement will permit extra light to show on one side. For very fine lines, such as on a scale, (*b*) is very good. Martin notes that the making of such readings depends essentially on the photometric estimation of small changes in the amount of light on each side of the index mark. A sense of symmetry is probably also important. Lambertz examined the arrangement of a scale and index mark designed to give the greatest precision when the index mark was made to coincide with any line of the scale.[(14)] In such scales the unit marks and the index marks are sometimes drawn in the shape of an acute isosceles triangle, and the apex of the index mark is placed opposite the apex of any desired mark

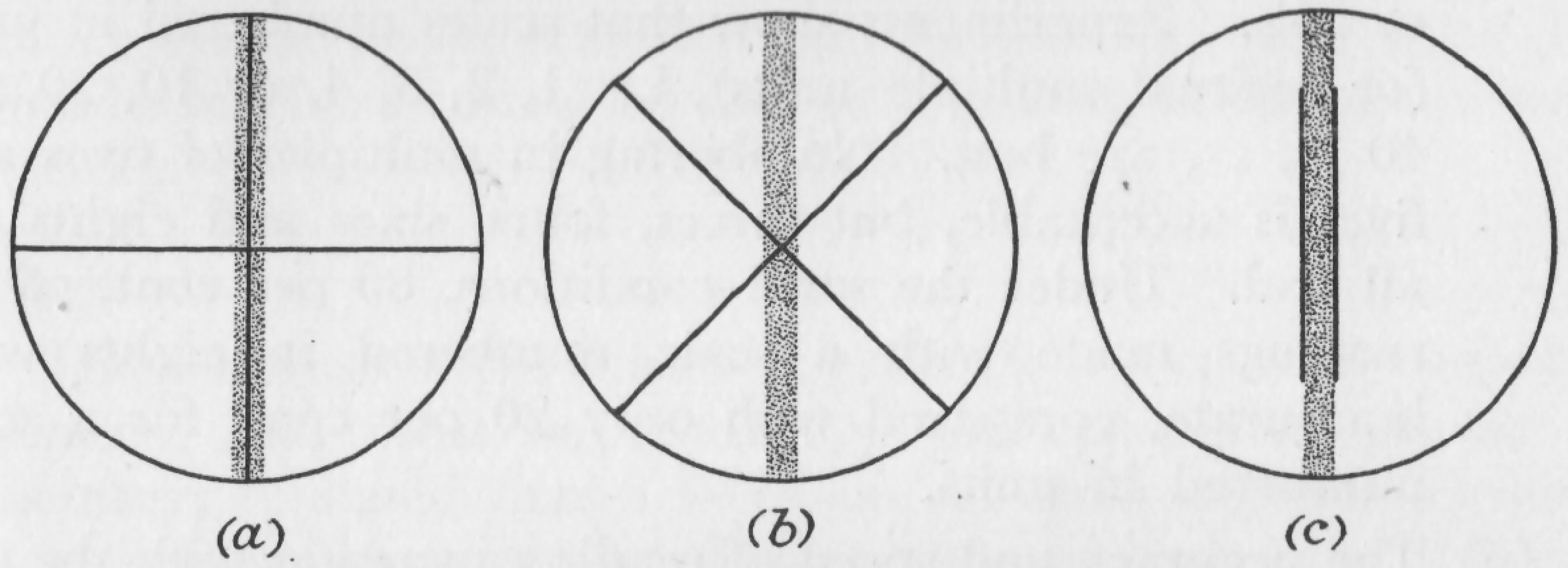

FIG. 64. *Setting of Cross-wires.*

Courtesy of Messrs. Blackie and Son, Ltd., and Professor L. C. Martin.

on the scale. This arrangement only gives poor accuracy unless the two apexes are exactly touching, a condition not very easy to satisfy. The accuracy is less critically dependent on the precise adjustment of the index mark to the scale when the apexes of the triangles are truncated.

The design of instrument scales or dials for obtaining numerical readings rapidly and accurately has recently received considerable attention. This question is very important for aircraft instruments, when several dozen dials may be displayed on a single panel, but the lessons learnt are certainly applicable to graticule design. Murrell has summarized much of the published work on this subject, and gives the following findings.(15)

(i) Bad numbering of dials often leads to inaccuracy. Scales are spoiled when the main markers are numbered in 15's or 25's. Experiments show that scales numbered in units (or decimal multiple units), i.e. 1, 2, 3, 4, or 10, 20, 30, 40 . . . , are best. Numbering in multiples of twos and fives is acceptable, but threes, fours, sixes and eights are all bad. Under the same conditions, 80 per cent. of the readings made with a scale numbered in eights were inaccurate, compared with only 20 per cent. for a scale numbered in units.

(ii) The accuracy and speed of reading increases with the size of the scale, until the graduation interval subtends an angle of 10 minutes at the eye. This is a critical size, and no further improvement is made by increasing the size beyond this point.

(iii) The accuracy is not improved by increasing the number of graduations beyond the point where the desired sensitivity is obtained by interpolating to divide one scale division into fifths. Visual division into fifths is definitely more accurate than division into tenths.

Murrell suggested the following rules for guidance in designing divided scales.

(*a*) Use the simplest scale possible, with the number of divisions just sufficient for the scale to be read with the accuracy required.

(*b*) Intervals should be numbered in ones, twos or fives (or a decimal multiple of these), using the lowest possible number of figures, to avoid overcrowding.

(*c*) The number of subdivisions should be a minimum, and never more than five between numbered divisions.

(*d*) The graduation interval should, whenever possible, be interpolated into five parts.

Specifications for the relationship of the thickness and length of the dividing lines to the graduation interval are given, as are suggestions for the size and shape of the figures.

Murrell also stated that unnecessary details such as maker's name, type and purpose of each scale, etc., should not show on the dial itself, and that the best dials are those with the clearest and fewest markings consistent with the observations desired. He concluded :

"Dials designed with this in mind will do full justice to the quality of the instrument and will lighten the task of the user, when he has been convinced that he is getting value for his money in a dial not crowded with graduations."

Line Width

The thickness of the lines of a graticule is a critically important property, and must be related to the capabilities of the eye. Rheinberg (8) stated that a 0·001-in. (25 microns) line viewed at 10 in. subtends an angle of 20 seconds at the eye, and this is too narrow for comfortable observation. About twice this width is the lower tolerable limit. When scales are viewed with a ×5 or ×8 ocular, a line thickness of 0·0005 in. (12 μ) is sufficient. He also stated that the thickness required depends on the circumstances in which the graticule will be viewed. An opaque line seen against a white background looks narrower than it really is, whereas a transparent line seen against a white background looks markedly narrower than an opaque line of the same width. Transparent lines do not need to be excessively fine, since objects seen through them can be centred with great accuracy.

Rheinberg's opinions about the lower tolerable limit of line width are supported by experiments done later by J. Guild, who measured the errors (or insensitivity) obtained when observers had to set a cross-wire graticule on a fine line.(16) As the thickness of the line was decreased, so that it subtended less than 40 seconds at the eye, the insensitivity of the measurements increased rapidly. With increasing line width the sensitivity remained substantially constant when the wire subtended between 60 and 120 seconds, and then gradually decreased with further increase of thickness. The fall of sensitivity with widths below 40 seconds was explained in the following way. The eye does not actually see the wire but perceives the two bright areas on each side which are separated by the image of the wire. When the wire is too narrow, the light diffracted from these areas into the geometrical image of the wire overlaps from each side, with resultant loss of image contrast and discomfort. In fact, the edges of the images of the bright areas on each side are no longer properly resolved. Guild also showed that the inaccuracy of setting of the position of the rather wider lines corresponded to an angle of only 2 seconds, or about one twenty-fifth of the resolution of the eye!

The designer must also remember that a lower limit to the line thickness which can be made is set by the limitations of the production processes. It may happen that the user will demand lines of such fineness that it would be necessary to use an objective which could cover only part of the field. A decrease of field size or an increased line width may then be required. In this connection, it should be remembered that a larger field can often be reproduced more satisfactorily if the lines at the edge of the field are arranged radially with respect to the axis of the objective (Chapter 5). Difficulties in production can also be caused when the design includes lines of different thickness (Chapter 9), and it may prove helpful to break the heavy lines into dots. Another complication is that all lines tend to become thickened by many photographic-reproduction processes, and the proportional increase is greater with the fine lines. Rheinberg has actually published figures indicating the percentage increase obtained when producing lines of different thickness, and suggests that the drawings should be adjusted to compensate for this.(8) Such figures are determined by the individual properties of the objective and photographic process used, so that these data really only illustrate the principle, and the reader should prefer to use figures obtained from his own observations.

Graticules are usually made with black lines on a clear background, but white or highly reflecting lines, or transparent or coloured lines may be required for use with special types of observation or viewing conditions. Reflecting lines have been used for observations at night, when the general illumination is inadequate to show black lines clearly. Transparent lines are convenient when no part of the observed object must be obscured, while the extra discrimination given by coloured lines can lessen eye-strain. They may also avoid confusion when comparing two scales, such as in the use of a stage micrometer for calibrating an eyepiece scale.

(2) *The Method of Illumination of the Graticule*

Many graticules are simply illuminated by the light coming from the field being observed, but auxiliary methods have to be used when the field is dim. Thus, "silver-line" graticules, in which the lines appear like narrow strips of mirror, have been lighted by a small lamp in the optical instrument itself. Glass-etched lines can be made to appear self-luminous by shining light into the edge of the glass bearing the image, so that no direct light enters the eyes. Graticules for use at night can also be made with a phosphorescent material, or with a fluorescent material illuminated by ultra-violet light.

The use of green light when making an exacting series of observations has been recommended. Nebe described experiments in which eye-strain was materially lessened by viewing the graticule through a green filter.(17) It may also sometimes be convenient to alter the visual contrast of a graticule by using a coloured image and varying the spectral composition of the light. The same effect could be obtained by making the image from a polarizing material of the type used in "Polaroid" Vectographs, and rotating a polarizing screen in the eyepiece.

(3) *Dimensional Accuracy of the Scale*

The requirements for dimensional accuracy in graticules vary greatly according to their type and purpose. Thus in sighting graticules and cross-wires the main requirement is that the line width be kept within certain limits, and errors in size of the order of one per cent. would hardly be noticeable. Stage micrometers and other types of measuring or eyepiece scales for use with a microscope should have smaller errors, and it would seem reasonable to expect the overall length of such images to be within 0·1 per cent. of the stated value. Distortion in the objective used for producing the images may cause the individual graduations to vary slightly, but this will normally be of little consequence in view of the image distortion likely to be introduced by the microscope with which the graticules are used. The accuracy of visual estimates of size obtained by superimposing a divided scale on the image of an irregular object (often without sharp edges) is, in any case, not high, and a precision of one per cent. can be considered quite good for such measurements.

The highest possible accuracy is required for divided circles and similar large graticules used in theodolite and measuring instruments. Thus with a 4-in. diameter (10-cm.) divided circle, 0·00004 in. (1 μ) at the circumference is equivalent to four seconds of arc, and an accuracy of one second of arc has been claimed for instruments using such scales (see above).

The dimensional accuracy of photographic graticules is determined by the accuracy and stability of the original drawing, by the absence of distortion in the objectives used at all stages, by the alignment of the apparatus and correct centring of the image on the axis of the objective, and by the dimensional stability of the emulsion layer in which the image is formed. The dimensional stability is likely to be best when the emulsion has adequate adhesion to, and is kept permanently on the support on which it is exposed. Excessive swelling during processing should be avoided. Additional precautions which may be adopted with gelatin emulsions are to form the image so that no part is less than 0·4 in. (1 cm.) from the edge of the plate, and to condition the emulsion before exposure to relieve stresses in factory-dried emulsions (Chapter 4).

Dimensional stability of the emulsion is particularly important when the final graticules are made by contact printing, since mass-production methods may involve the making of a succession of " master " negatives and positives, and errors can creep in at every stage.

(4) *Cleanliness in the Background*

There is a tradition, probably originating from the days when graticules were made mainly by ruling on glass, that graticule images should be absolutely flawless. Although such an immaculate standard can be admired as a praiseworthy goal, it can greatly

increase the cost of the industrial-scale production of graticules. It is therefore not impertinent to inquire what effect flaws can have on the use of a graticule. Flaws may take the form of breaks in the lines of the image itself, which may have a distracting effect and, if unsymmetrically positioned on the line, can actually cause an error when setting cross-wires on the line. With graticule images small enough to be formed by a single exposure, the avoidance of line breaks is largely a matter of inspection and acceptance of a moderate rejection rate due to this cause. Line breaks can, however, cause great difficulty in the making of large images, or of images built up from many individual exposures (see below).

Greater difficulties are generally caused by dirt in the background, and this mostly consists of transparent particles with a refractive index different from the mounting cement. Their effect depends greatly on the conditions used for illuminating the graticule. If the graticule can be illuminated with a wide cone of rays, such as on the stage of a microscope, the visual contrast of the refracting particles will be relatively low and they may not be too noticeable. The same particles illuminated by the narrow cone of light entering a microscope eyepiece may appear quite black, and interfere seriously with such operations as particle counting.

The rejection rate resulting from dirt depends both on the size of the graticule and the magnification at which it is viewed. With stage micrometers one or two dirt particles in the field can ruin the image because it is viewed at high magnifications, but the area of the images is so small that there is a good chance that no dirt will be found in the image area. Higher rejection rates are likely to occur with larger scales viewed at a moderate magnification. These difficulties have stimulated work on processes giving a stencil image with the background devoid of colloid, and thus unable to hold any dirt particles.

It seems probable that the difficulty of reconciling the conflicting requirements of cleanliness in the images and low production costs could often be eased by closer co-operation between the makers and users of graticules. In cases where minor blemishes will not interfere with the use of the graticule, users might be persuaded to accept a less immaculate scale at a fraction of the cost of a perfect image.

(5) *Nature and Specification of the Support*

In some cases, graticules can simply be made by producing an image on a photographic plate, cutting out the area containing the image and edge-grinding the glass so that the image is correctly positioned. The glass bearing the graticule may, however, have to conform to exacting specifications with respect to thickness, size, absence of strain or bubbles, flatness and parallelism of the two surfaces. The image may sometimes even be required on a curved surface. It is thus often the practice to prepare and test the blanks before they are coated with any photographic " emulsion ". When graticules are made on prepared blanks, special jigs are often used during exposure to ensure that the centre of the scale coincides with the centre of the blank within a very small tolerance.

(6) *Nature of the Material forming the Pattern*

The image of a graticule may take the form of a pigment suspended in a colloid layer, a stencil image in the colloid layer, a stencil image in some other layer applied to the support or may even consist of markings etched into (or right through) the base material itself. These diverse forms are described in later sections of this chapter. We should, for the moment, only note that choice of an appropriate process is most important since it influences the resolution, background cleanliness, amount of retouching needed, robustness of the image and the production cost.

(7) *Resistance to Adverse Handling*

Most graticules, and particularly those used for military instruments, are likely to be exposed to rough handling. They may be subjected to mechanical shock, Arctic or tropical conditions, to high humidities which can permit fungi to grow on the glass itself, and to salt water, dust and sand. Moreover, a graticule will be of little use if the surfaces cannot be polished at intervals to remove dirt and smears. In many cases, satisfactory resistance can be obtained by covering the graticule with a cemented cover-glass, with the image left imbedded in the original colloid layer in which it was produced. This type of graticule should be able to show the full intrinsic sharpness of which the emulsion is capable. The substitution of thermosetting resins of suitable refractive index for Canada balsam should make the use of a cover-glass more acceptable

than it has been hitherto. Graticules in which the image consists of a stencil on the surface of the glass tend to be damaged when wiping and the resistance may be improved by " burning-in ". Heat treatments can be used either to insolubilize the colloid stencil or to burn away the colloid and " sinter " the pigment on to the surface of the glass.(18)

The most resistant scales of all, however, are undoubtedly those in which the image is actually etched into or right through the base. Graticules in which a photomechanical process gave an image etched into the glass were widely used in the Second World War. Towards the end of this period, metal graticules were also used, and these had the pattern etched right through the base but still showed very sharp edges.

(8) *Special Physical Properties*

Techniques of the type used for producing graticules can also be used for making articles in which some special physical property is more important than the visual appearance. Thus, graticule processes were used by Gresham and Loening for making fine images of electrolytically deposited copper on film base, and these were to be used as electrical resistors for use in strain measurements.(19) In this case the electrical resistance of the image, and the changes of resistance obtained on stretching the film base were all important. The same authors used a variation of this process for making fine metal grids with meshes of up to 300 lines/in. These were used for components of radio equipment and as grids to support specimens in the electron microscope. The mechanical properties of the images when removed from their original support were important in this case. Microphotographic images have also been made radioactive for testing the resolution of emulsions used for autoradiography (Chapter 13). It seems probable that graticule processes could satisfy other needs for minute articles with intricate shapes, and the potentialities of these processes should be more widely known.

(9) *Influence of Design on Price and Production*

Consideration of the factors in design already discussed will have indicated the general form of a graticule, but some of the decisions may have to be modified to permit economic production.

The methods used in production should be related to the number and rate of output likely to be needed. Some production methods will lend themselves better to periodic revision of the design, such as may be necessary with graticules used in military instruments. Rheinberg (8) pointed out that quite trivial matters may influence the cost of the graticule. Thus, the substitution of a 0·4-in. (10-mm.) disc for a 0·6-in. (15-mm.) disc may increase the cost by 5 per cent. A substantial increase in cost may also result if the lines are required to go right up to the edge of the disc. While photographic methods make it almost as easy to produce a complicated instead of a simple pattern, the cost of " spotting " and retouching the latter may be much higher.

The greatest differences in the cost are, however, probably made by the standard of cleanliness required in the images. The higher the standard demanded the more careful and costly will the inspection of each image have to be, and costs can also mount alarmingly if the rejection rate for the finished graticules is high.

(10) *Suitability of Photographic Methods*

Although photographic methods have been developed to the stage where they can be used for making most types of graticule, it would be absurd to overlook the fact that they have their limitations ; or that, in some cases, mechanical ruling would be superior. Mechanical dividing-engines, for instance, have been used to produce rulings with up to 100,000 lines per inch (4,000/mm.) : (20) a fineness never achieved by photographic methods. Mechanical ruling also permits a given fineness of line to be obtained over larger areas than can be covered by objectives of any known type. Thus diffraction gratings with 15,000 lines/in. (600 lines/mm.) have been made over 6 in. (15 cm.) long and with a width of several inches, whereas photographic methods could give a comparable sharpness over a circle of diameter no larger than 0·04 in. (1 mm.). When very large scales are required with fine lines, a combination of photographic and mechanical dividing methods can be used (see below). The final scales, nevertheless, may be produced by contact printing from a mechanically-ruled master scale, or from a photographic master built up by projecting successive small elements of the image side by side.

There is less point in using photographic methods if the graticules are to have a very simple pattern readily made by a pantograph or dividing-engine, and particularly when only a few images of the same design are required. One advantage of the mechanical methods is that there is essentially only one operation in making the images, and this saves the retouching and inspection at several stages needed when making etched graticules.

Production Methods

The images of many graticules are formed essentially by conventional photographic methods, but in others more or less complex photomechanical procedures are used to provide images with properties quite different from the image formed by the original exposure and development. It is, in fact, convenient to think of graticule production as being divided into two stages. All graticules have to pass through the first (photographic) stage, but only some of them go on to the photomechanical stage.

Photographic Stage

Drawings and Master Negatives

The first stage in the production of most graticules is to make a drawing of the image required, often at 50 or 100 times the scale of the final graticule. Special attention is usually needed to ensure that the width of the lines will be within the tolerances set by the designer, and as already noted, it may be necessary to reduce the relative thickness of fine lines in the drawing, to compensate for line spread in photographic reduction. Smethurst has made a number of interesting comments on original drawings, and bases these on his experience in making graticules to the specification of commercial or Service customers.(21) In Great Britain it is not uncommon for complete drawings ready for copying to be submitted by a customer. This is likely to lead to trouble unless the customer is familiar with the peculiarities of the production process. He therefore preferred to make a token charge for producing a drawing from a " blue-print " submitted by the customer. When accepting a new job it is advisable to ensure that the image is not laterally reversed (there may be no obvious indication of this) and whether dimensions which may be marked in inches have been converted correctly from the metric units probably employed by the designer. A conversion factor of 25 millimetres to the inch (25 microns to the " thou ")* is commonly used instead of the more precise figure of 25·4, and the resultant error may be outside the tolerance for size set by the designer of the instrument.

Smethurst stated that drawings made at fifty times the final scale may not be large enough, when fine limits are set for the tolerance of line thickness. Really fine limits are usually specified only for the central part of the image, which may accordingly be drawn on a still larger scale, and reduced to provide a photographic print which can be pasted into position on the drawing of the rest of the scale. With the aid of a magnifier, it is possible to align the images within 0·001 in. (25 μ), which will correspond to a very small error after reduction. Shadows at the joins of such a composite " drawing " can be concealed with gummed paper and Chinese white, and minor blemishes such as compass pricks can be removed by retouching the negative. In fact, the visual appearance of the drawing is quite unimportant, since its only function is to be photographed to provide a master negative. Draughtsmen new to this work may make a poor job for lack of understanding of this point, and should be instructed to concentrate their attention on essential details rather than on " prettiness ".

A meticulous technique for the production of original drawings is employed at Möller's graticule factory.(22) The drawings are made on a white baryta-coated paper fixed with gum arabic to a rigid glass, metal or wood support to minimize distortion or the changes of scale which paper drawings show as the humidity varies. The drawings are made on special linear or circular dividing-tables, in which a bow pen slides in a holder supported from an overhead girder. One operator moves the pen, and another moves the holder by the required amount between the lines. Attention is given to several details influencing the appearance of the final image. Thus, the lines are drawn rather longer than desired, so that the ends can be made square by ruling over them at right-angles with white paint. The figures are drawn separately and are stored as prints on bromide paper which bear registration marks so that the correct orientation can readily be found. The appearance of certain figures such as a 4 and 8 is found to suffer from thickening of the lines where they intersect. This defect of photographic reproduction by a lens system is counteracted by reducing the line thickness sharply in the drawing at the point of intersection (*Figure* 65).

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* Called a " mil " in the United States of America.

Special measures are needed when the accuracy required in the final graticule is so high that a drawing at a scale of ×50 or ×100 produced by conventional methods cannot meet the specification. While drawings of improved accuracy can be obtained by an apparatus developed by Lee at the National Physical Laboratory,(23) or by a " co-ordinatograph " on which a skilled draughtsman can reach a precision of 0·004 in. (0·1 mm.);(24) there are cases in which drawings of reasonable size could never give the required accuracy, and other methods (described later) have to be used.

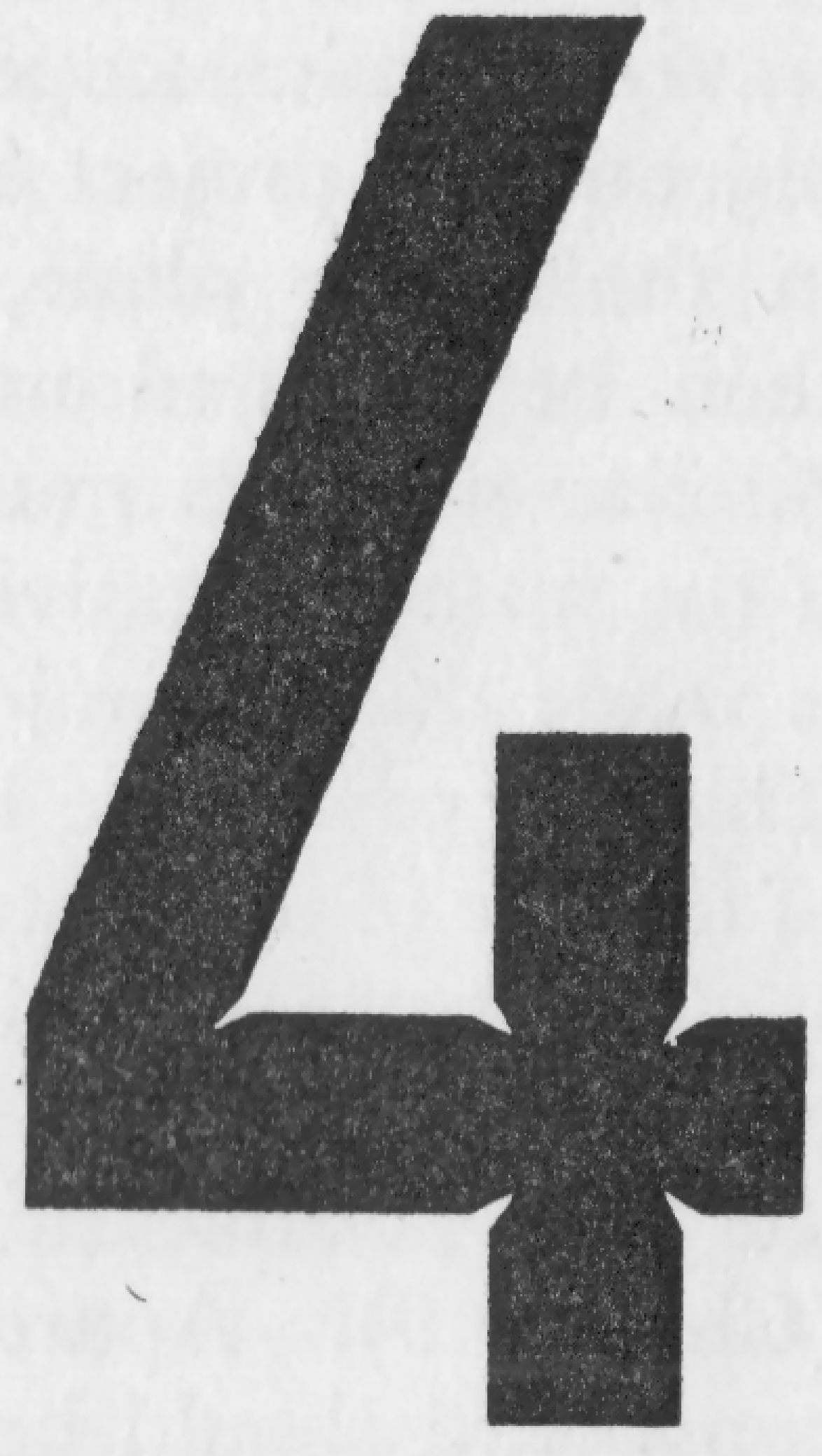

FIG. 65. *Compensation for Image Thickening at Line Intersection.*

In preparing master drawings in the Möller graticule factory, the width of the lines is reduced at intersections to compensate for thickening during photographic reproduction.

From B.I.O.S. Final Report, 1552, by permission of the Controller of H.M. Stationery Office.

Master Negatives made from Drawings

Graticules are generally made either by reduction from a master negative of size intermediate between the drawing and the graticule, or by contact printing from a negative of the same size as the final image. When graticules are made by contact, negatives are often used containing many identical images, produced by imprinting a series of successive exposures on different areas of one plate (" step-and-repeat ").

Whatever form the master negative takes, it is usually made from the drawings by photographic reduction in one or more stages, and care is needed to prevent distortion, to maintain the over-all dimensions within the required limits, to preserve the correct relative line width and to avoid blemishes. Exact parallelism of the image plane and the copyboard is essential, and methods already described in Chapter 7 can be used for aligning the equipment.

The size of the image in the master negative must be checked carefully if the final graticules are to be made in a fixed-reduction camera or by contact printing, since in both cases no adjustment of image size is possible at the final stage. This check can be made by using a microscope to compare the length of the reduced aerial image with a standard scale, or by measuring the length of the reduced aerial image or of a developed test image with a travelling microscope. Another convenient method is to use the objective to project an enlarged image of a standard scale, placed in the image plane, back on the copyboard. The camera can then be adjusted until the projected image is the correct size. Similar methods must also be applied during the final reduction, if the master negative is not sized exactly ; and the final adjustment is made during projection printing of the actual graticule images. This last procedure leaves nothing to chance, but precise checking of the size of really small images can be quite difficult and laborious.

The basic techniques used for preserving the correct relative line width in master negatives are similar to those used for securing the best possible line quality in other extreme-resolution images (Chapter 9). Apart from the precautions already prescribed, the copyboard should be evenly illuminated and the plates should be given no greater exposure than the minimum required to produce an adequate working density in the background. If heavier exposures are used to obtain a completely opaque background, it may result in no further increase in the contrast of the final images, but can introduce image spread.

The emulsion should be chosen to give a really sharp image of the narrowest line required, and " process-type " plates are very convenient for producing line widths down to about 0·002 in. (50 μ). Some graticule producers have found " lith-type " plates, which give exceptionally high contrast when developed in the appropriate solution, useful for making master negatives, as they give images with exceptionally clean edges without cutting or intensifying. Wet-collodion or concentrated-Lippmann emulsions are mostly used for making the finest master negatives, the latter being particularly suitable for long production runs by contact printing, when fresh working masters have to be made at intervals from intermediate contact positives.

If the negative consists of narrow transparent lines on a clear background, pinholes can easily be blocked out, but refracting particles in the background of a negative with large clear areas present a more difficult problem. Their influence can be partially or completely eliminated by mounting a cover-glass over the negative with Canada balsam (or a similar medium), or by making contact prints with the air-space between negative and printing emulsion filled with an immersion fluid, or by using a stencil process for making the negative so that the colloid is washed away from the transparent areas (Chapter 3). The time and care expended on a master negative give it a considerable value, and the firm of Möller therefore stabilize the image by converting it to silver iodide (Chapter 4). For the same reason it is advisable to make at least two masters, once the camera has been set up, to guard against loss or breakage.

Master Negatives produced on a Dividing-engine

The method of producing master negatives by optical reduction from a drawing is no longer practicable when graticules are required with a length of several inches and with the position of each line accurate to a micron or so. Geiser(25) has graphically illustrated the dilemma by considering the production of a 4-in. (20-cm.) diameter circle divided into 10 minutes of arc by lines 0·0003 in. (8 μ) wide. If a drawing were made to only 25 times the final scale, it would have to be inconveniently large (over 8 ft. (2·5 metres) in diameter), and contain 2,160 lines only 0·008 in. (0·2 mm.) wide. It is impossible to draw satisfactory lines of this width, and even if they could be drawn they could not be positioned with the necessary accuracy. He therefore concluded that such repetitive patterns are best made with a dividing-engine. A diamond can be used to rule lines of width from 0·003 to 0·0002 in. (75 to 5 μ) on silvered glass, to provide a negative from which the final images can be made by contact printing.

A similar method was considered by Burmistrov, who investigated layers which might usefully be applied to the glass before ruling.(26) Developed emulsion layers, smoked glass, or chemically-deposited or sputtered films were all tried, but tended to crack or crumble on ruling. A lead-sulphide mirror adhered to glass with the tenacity necessary for his purpose.

An interesting technique for speeding up the production of master negatives on dividing-engines is to mount a photographic plate on the instrument so that it can be traversed underneath an objective and record a whole succession of images side by side.

Consider, for instance, the circle referred to above. The circumference of the scale is rather more than 11 in. (28 cm.), and this means that each degree fills a space about 0·03 in. (0·78 mm.) wide. This is smaller than the useful field of a 1-in. (25-mm.) achromatic objective, which should give a satisfactory image divided directly into 6, 60 or even 120 spaces (each space representing 10 minutes, 1 minute or 30 seconds of arc respectively). A composite circle can then be made by rotating the table on which the plate is mounted a degree at a time, and projecting a one-degree unit of the scale at each position.

A similar principle is being developed at the National Physical Laboratory for the production of large linear scales, with an accuracy of the standard normally reserved for diffraction gratings.(27) This accuracy is secured by use of the " Merton nut ", which consists of strips of cork clamped round a very fine and accurate screw having 5,000 threads to the inch. The resilience of the cork enables the position of the nut to take up the average position of a great number of turns of the thread, thus eliminating periodic errors. Rotation of the threaded bar in the nut is used to move a photographic plate under the reduced image of a narrow slit, and a cam on the bar operates a micro switch at predetermined intervals, causing a flash of light which imprints an image of the slit on the emulsion. In this way, large linear scales can be produced with each inch divided into 5,000 parts or any convenient sub-multiple of this number.

The flexibility of this type of procedure is illustrated by another example in Geiser's article.(25) A code wheel was required by the Bell Telephone Laboratories, which would count in a binary system, and hence permit photoelectric scanning to provide intelligence of the position of the shaft bearing the wheel to one part in 8,192. For this purpose an image was made with thirteen consecutive rings, with the innermost divided into black and white semicircles, and other rings divided respectively into 4, 8, 16, 32, . . . 8,192, alternating black and white segments. The resulting pattern could be considered as a circle divided into 8,192 sectors, each with its unique combination of light and dark patches contributed by the thirteen rings. The " master negative " consisted of thirteen wedge-shaped windows, and the optical system projected reduced images of these so that they occupied the width of one component sector of the image. A bank of relays controlled the opening and closing of each window needed to produce the required combination of light and dark patches for each of the 8,192 positions in which the plate was exposed. Even though the complete cycle of operations was mechanized, it took 21 hours' operation to expose a single plate. This remarkable achievement (*Figure* 66) would appear to justify Geiser's contention that the range of patterns which can be generated in this way with linear or circular dividing-equipment is almost unlimited.

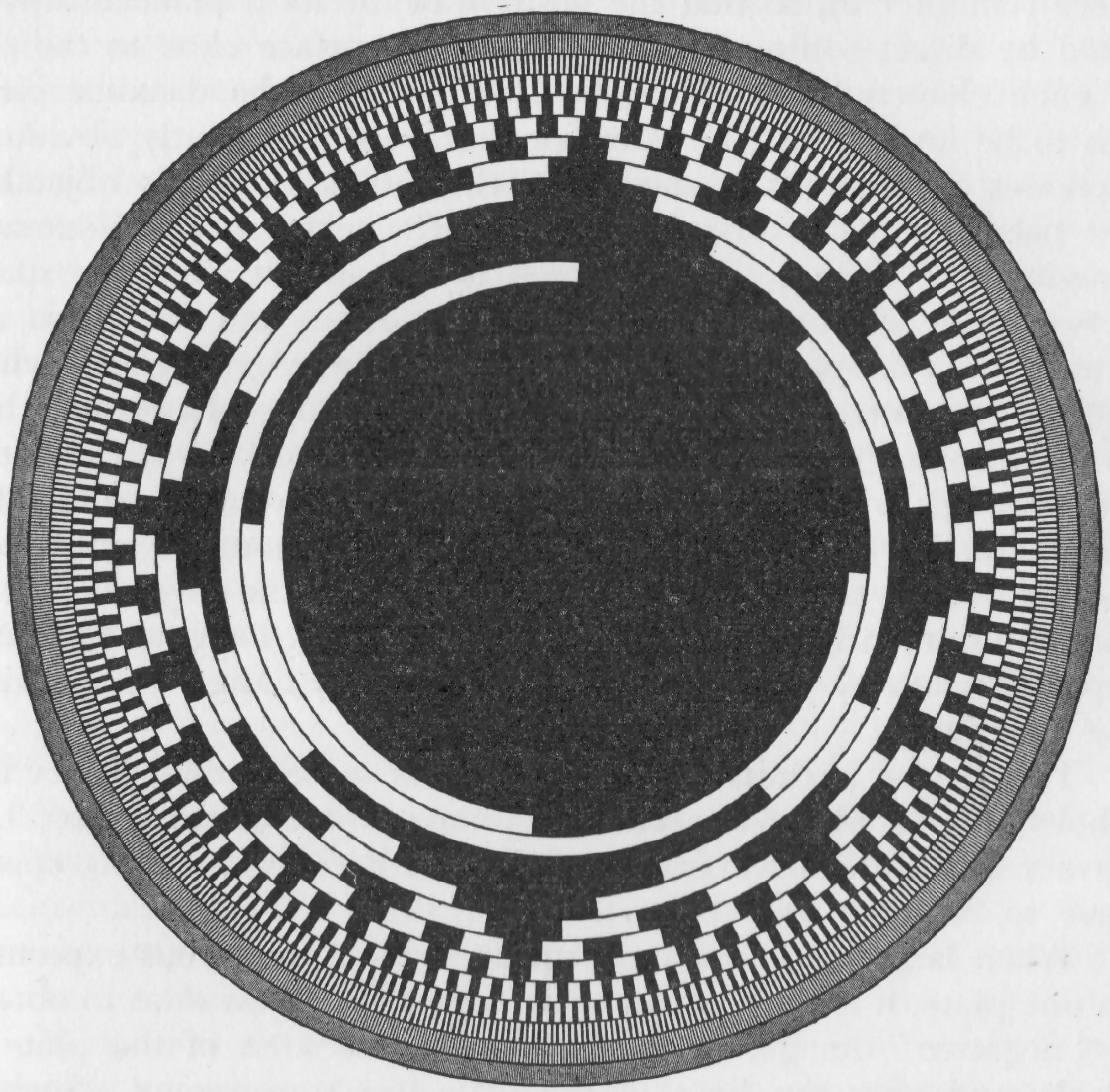

FIG. 66. *Graticule obtained by exposing Plate on Dividing-Engine.*

Composite image produced by repeated exposure of plate to reduced image of slit behind which operated 13 electronically controlled shutters. Exposure of the master negative took more than 20 hours.

Courtesy of Mr. R. D. Geiser. Messrs. W. and L. E. Gurley, Troy, U.S.A.

Although the building-up of complex images by combining a dividing-engine and a graticule camera is clearly a valuable technique, the very size of the images makes it difficult to ensure uniform sharpness over their whole area. Any lack of flatness of the emulsion surface is more likely to lead to serious errors of focus. These can be eliminated by fitting the objective with a salt-cellar distance piece (Chapter 6), so that the position of the focal plane is always fixed by direct contact with the emulsion surface close to the site of each element of the image. The fact that the distance piece has to be lowered on the emulsion surface so frequently obviously increases the danger of damaging the emulsion. This objection has been avoided by Bovey, by using the principle of pneumatic gauging.(28) A filter pump is used to extract air from the space between the objective and the distance piece, and the static air pressure in this space is recorded on a manometer. At first, when the air can enter freely, there will be no change of pressure, but as the distance piece approaches the emulsion surface, it closes the gap through which air can enter, and the internal pressure falls. The reduction of pressure registered by the manometer is, in fact, a most sensitive indication of the distance of the objective from the emulsion surface, and it permits the correct focus to be found repeatedly at any point on a plate without any danger of abrading the emulsion.

This device permits uniform sharpness to be obtained over the whole area of plates on ordinary photographic-quality glass, but further difficulties may arise from lack of flatness if contact copies have to be made (see below).

When large scales are built up by making numerous exposures on one plate, it is often useful to arrange the process so as to obtain a " negative " image, in which most of the area of the plate is black, and only the lines of the scale are transparent. Such a result is required when the final images are to be printed directly from the first master negative, in order to avoid the risk of spoiling image quality by multiple-stage contact copying.

Now on direct development, concentrated-Lippmann emulsions give a " negative ", so that the desired tones will be obtained by projecting a " positive " transparency. The field covered by each element of the exposure is, however, likely to be so small that the blackened area containing the images is confined to a narrow strip or circle on the plate, the remainder of which remains unblackened. Blocking out the background with an opaque medium on the emulsion is not recommended (Chapter 10), but the desired result can be obtained in other ways. One method is to expose the plate to a positive transparency, and then develop, treat with an acid-stop bath (Appendix I, B), and wash and dry *without fixing*. The area of the plate containing the images is then carefully painted with a waterproof lacquer (such as " Peridak " staging paint), and the unblackened areas are completely developed by immersing in a developer by artificial light. So long as the lacquer does not extend beyond the edges of the developed images, this procedure causes the background to blacken completely. In the meantime the transparent lines have been protected by the lacquer, and the process is completed by removing the lacquer with the recommended solvents, followed by fixing, washing and drying in the usual way.

A more direct method for achieving the same result is to expose to a " negative " transparency, so that the lines first develop black, and then reversal process to give a negative by bleaching and re-developing (Appendix I, A). Both these methods are likely to result in some loss of sharpness, but the influence of lens flare in the first may prove less harmful than the heavy exposure needed to give clear whites with reversal processing (Chapter 4).

Sensitization of Plates for Graticule Production

We have already seen that graticules often have to be produced on prepared glass blanks which have to be sensitized individually. Bichromated-colloid layers going right up to the edge of the blank can be applied by means of a centrifugal " whirler " and this method is also used for coating albumen layers. The application of the thicker emulsions used for silver-halide " dry-plate " processes is less easy, and the results have sometimes been spoilt by the change of emulsion thickness caused by the formation of a meniscus at the edge of the blank. Rust described a method for avoiding this difficulty, in which six circular blanks were placed in accurately-machined apertures in a metal plate having the same thickness as the glass, and the whole assembly was coated as a single unit.(24) After drying, the coated blanks were cut from their matrix by pressing against a cutting-plate containing sharp-edged holes slightly larger than the glass blanks. An alternative method for obtaining reasonably uniform layers right up to the edge of a glass blank is suggested by the procedure used for applying stripped emulsion layers when making autoradiographs (Chapter 13). This has the advantage that it should enable the graticule producer to apply a reproducible coating to his own blanks, or to re-coat blanks from which rejected images had been cleaned off. The same method should also permit substantially uniform layers to be applied to moderately curved surfaces.

An economical method is used by Möllers, in which multiple images are made on temporary supports, and at the completion of processing are transferred to the final blanks.(29) This procedure certainly introduces the risk of image distortion or alteration of dimensions during transfer, but the fact remains that this firm have worked it successfully for many years. In many cases, however, it may prove more convenient and cheaper to produce the graticules directly from an industrially coated concentrated-Lippman emulsion.

Another method particularly suitable for coating large glass blanks is described in Chapter 3, in the section dealing with iodoform-sensitized phenol-formaldehyde resins.

The Exposure

Graticule images are made either by projection printing or contact printing. Projection printing is only convenient with the faster microphotographic emulsions, since each image has to be made as a separate operation. This method has the advantage that only one master negative is needed, and this is not subjected to the wear and tear inevitable in contact printing. Moreover, the master negative is usually substantially larger than the final images and is correspondingly easier to spot or retouch. Changes in the design of the image will also only cause a slight interruption of production with projection printing, whereas they can cause complete dislocation with contact-printing methods. Projection printing implies not only that the images have to be made individually, but that a separate camera has to be used for each type of graticule being produced at any one time. The proportion of the cost of each graticule represented by the exposing operation is therefore likely to be higher than with contact printing, but this may only be a serious consideration when very large numbers of each type of graticule are required. Apart from the limits imposed by the speed of the emulsion used, the finest line which can be produced by projection printing is a function of the field which has to be covered (Chapter 5).

Projection printing is practically essential for the production of graticules with line widths much below 0·0002 in. (5 μ), when the difficulties of making satisfactory contact copies are great. High degrees of reduction can be conveniently used for the making of very fine images, and condenser illumination will hence give a very high image brightness permitting the use of some of the slower extreme-resolution emulsions (Chapter 8).

Contact-printing methods can always be used, however slow the emulsion, and lend themselves to the rapid production of large numbers of images from multiple negatives containing dozens of units. They also provide the only practicable means for duplicating large images with fine lines, by printing from a master negative made on a dividing-engine. Contact printing also assists in maintaining a high standard of uniformity with respect to the dimensions of the image, and in permitting substantially identical images to be made in separate factories.

Although contact printing is an essentially simple operation, certain details require care when making graticules. If the images are made on previously edge-ground blanks, the negative must be held in a jig which locates the image relative to the edge of the blank within the tolerance specified by the designer. In order to ensure satisfactory sharpness, it is usual to employ a vacuum or pressure frame to press the negative and emulsion surface together. Even with a pressure frame there is a tendency for most of the pressure between the two surfaces to be supported by " high spots ", or by particles of dust ; and the surface of the negative may be easily damaged (*Figure* 59). It has been reported that after about a hundred exposures (or sometimes after only twenty) negatives may be so damaged that they have to be discarded. For this reason the original camera negative is often used only to make " master positives ", from which working master negatives are made. At one time Möller avoided damage to the negative by using thin spacers to separate the two surfaces, but has now abandoned the method.

In Chapter 10 it was shown that extraordinary results can be obtained if very fine negatives are printed with an appreciable separation between the surfaces. It is relatively easy to ensure satisfactory contact over a small area (say up to ¼ in. (6 mm.) square), but the problem becomes more difficult when the areas in contact are increased. Separation of part of the area resulting from lack of flatness of either plate, as well as dust, may reduce the sharpness. For this reason both master negatives and the final negatives may in extreme cases have to be made on plate glass or optical flats, and rigorous precautions against dust in the printing-room may be needed.

Exposing Emulsions on a Curved Surface

A number of interesting problems arise when the graticule image is needed on a curved surface. With spherical surfaces it has been the practice to produce a negative on a surface with a curvature complementary to that required in the final image. Thus a negative on a concave surface would be used for printing images on to a convex lens. The negative must, of course, be made by projection and it may sometimes be possible to obtain the necessary depth of focus by stopping down. If the work proved sufficiently important, however, it would be better to use an objective specially designed to give a concave spherical field. Schmidt optical systems should be useful for this purpose. Another difficulty is the distortion introduced by the use of curved surfaces for receiving the image, and the Wadsworth Watch Company have patented the use of a correcting lens to compensate for distortion even if the objective has a sufficiently great depth of focus.[30] Graticule images have also been printed directly from a flat negative on to a cylindrical surface. After sensitization of its outer surface, the cylinder is exposed by placing it opposite a narrow illuminated slit, and then smoothly pushing the negative between the slit and the cylinder so that it causes the cylinder to roll without any slip [31] (*Figure* 67). The slit is of such a width that only the area of the cylinder very close to the negative is exposed and hence the straight scale is, in effect, wrapped round the cylinder.

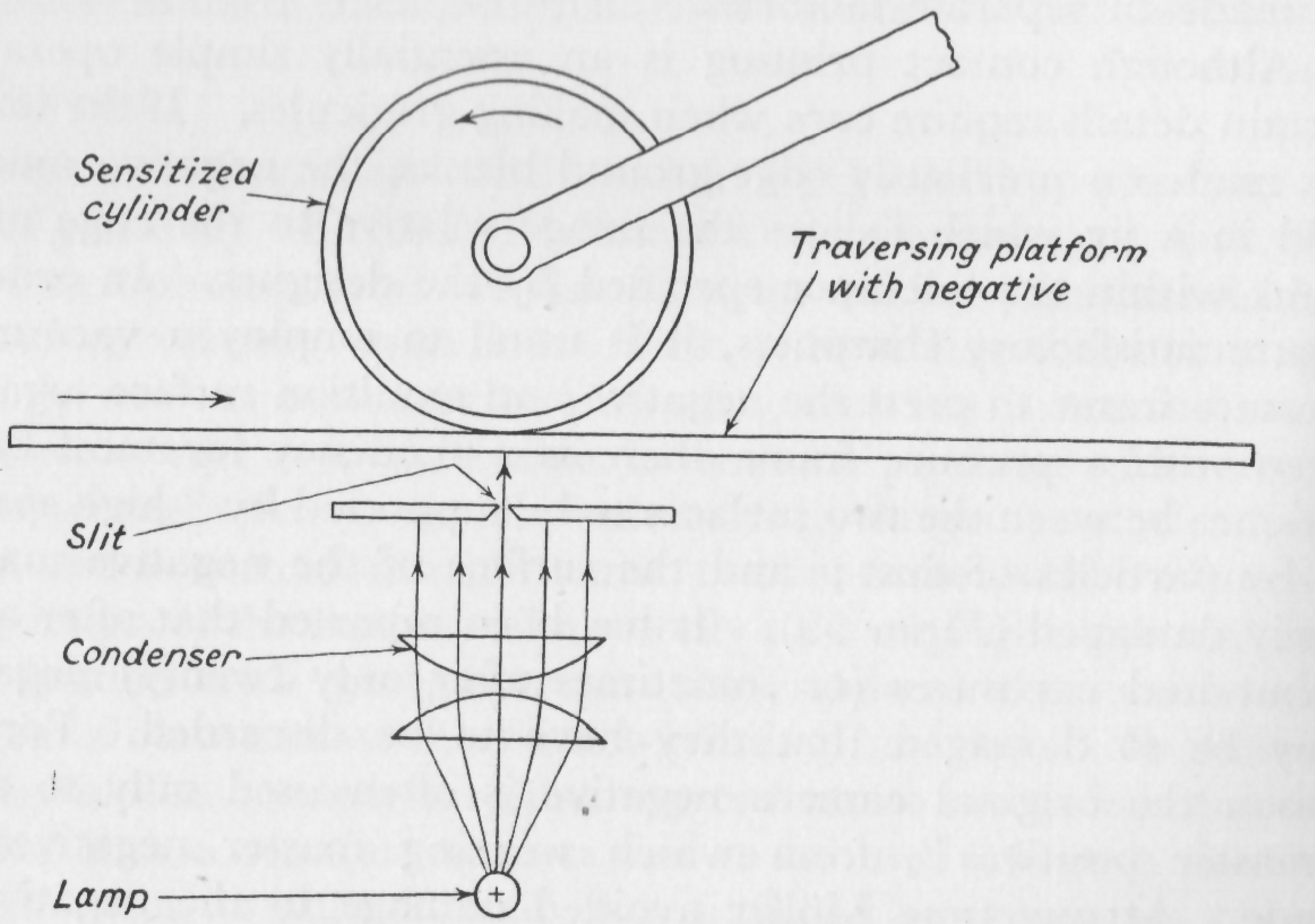

FIG. 67. *Printing Scale around Circumference of a Cylinder.*
Principle of equipment developed by the Royal Naval Scientific Service.
Courtesy of " British Journal of Photography ", and Mr. E. W. Jackson, M.Sc.

Processing

Processing methods used for making graticules are in general similar to those described in Chapter 4, but certain additional points have to be considered. The high value of graticules (even before processing much time may have been expended on each image), and the meticulous standard of cleanliness required, indicate that very stringent precautions are desirable. Bottles, measuring-graduates and dishes should be kept scrupulously clean, and filtration of the air supply, solutions and wash water will tend to maintain a low rejection rate. The risk of contaminating the images will be further reduced by methods of the type suggested in Chapter 4 for preventing dirt from reaching the emulsion surface. Since graticule work often involves producing many identical images over periods of months or years, special attention should be given to maintaining the activity of the solution and the time and temperature of development at a fixed level. To stint the developer is false economy, and the use of a fresh volume of solution for each dishful of graticules is likely to assist the production of consistent images. Each time a fresh volume of developer is compounded, it is a good plan to make a batch large enough for several days' (or even several weeks') work, and bottle in volumes sufficient for one day's use. A test may then be made to confirm that no change of development time is required when a new batch first comes into use.

The problem of handling a large number of individual units of plate or coated blanks can be solved by using racks to hold the plates, so that all the images processed at the same time can be transferred as a single unit from one solution to the next. Contamination of the emulsion during processing can be lessened by making the racks so that the plates are held vertical or upside down. Racks also lessen the risk of chipping the edges of glass blanks: an important point when blanks made to an exacting specification have to be used repeatedly because of a high rejection rate for the final images. " Perspex " is an excellent material for constructing racks, since it is easy to work, will not chip glass and has a satisfactory resistance to ordinary photographic solutions.

Photomechanical Stage

Modification of the Original Image

The specialized properties which may be required of different graticules are so numerous and varied that only a wide range of production methods could hope to satisfy them all. These methods mainly comprise processes of the type used in photomechanical work, and may involve modification of the photographic image so that all traces of its original composition are lost. In fact, a convenient way of obtaining a general picture of the methods possible is to consider the variety of transformations to which the original image may be subjected.

The image produced by the initial exposure and development may be:

(i) Used largely unchanged, except for a toning process to increase its stability or modify its optical properties.

(ii) The colloid may be washed off from either the exposed or the unexposed areas to form a stencil, possibly followed by a " burning-in " process to make the image more resistant.

(iii) The stencil image in (ii) may merely be used temporarily to protect the base material from etching by chemical or electrolytic action. The final design then consists of the marks made by the etching, and the original stencil image is removed from the surface of the final graticule. In some cases multiple stencils with more than one etching operation are used.

(iv) The stencil image may alternatively be used to protect the base from the application of further material which thus only reaches the base through the openings in the stencil.

(v) Very complex procedures, sometimes using operations of types (iii) and (iv) in succession may be used, particularly for making metal graticules.

Many different types of operation can be used in this work, and combinations of these can give an enormous number of possible procedures. A few examples will be used to give some idea of the range of possibilities.

(*i*) *Images used with relatively little Change*

A large number of gunsight graticules were made in Great Britain during the period 1940–5 directly on concentrated-Lippmann plates. One type consisted of a simple pattern of concentric circles with a very small central aiming spot. Working multiple negatives were made by " step-and-repeat " methods, so that 50 or more images could be contact printed at one operation from a single 10 × 8 in. (25 × 20 cm.) plate. After development and fixing, the gelatin of the emulsion was dyed a dark orange colour to comply with the specification for the instrument. When the plates were dry the individual images were cut out roughly and each had a cover-glass cemented on, and was finished by edge-grinding in the optical workshop when the cement had hardened sufficiently. Graticules with coloured lines have also been made from these plates by use of colour developers or chemical toning solutions. Many of Möller's graticules consist of the image stripped from the original plate, transferred to a blank and protected by a cover-glass without any modification of the photographic image.(29)

(*ii*) *Stencil and Film-less Processes*

Relatively resistant graticules have been made from silver-halide-gelatin emulsions by using the " etch-bleach " process to make a positive stencil (Chapter 4), and then heating to about 300° C. so that the gelatin was darkened and insolubilized.(32) Resistant stencil images can also be made by a photoceramic process and Rheinberg stated that Messrs. Adam Hilger Ltd. produced beautiful results by this process during the period 1915–18.(8) Möllers make very resistant graticules by platinum toning the silver image in their collodion film, and then heating to a temperature just below the softening-point of glass. This temperature is sufficient to cause the combustion of both the collodion and albumen in which the images were imbedded, and the platinum images are then effectively sintered into the surface of the blank. In this process there was a tendency for the blanks to be distorted during the firing process.(18)

Images have also been widely made by blackening the colloid stencil itself by one method or another. This may be done either by impregnating the original gum or glue solution with nuclei (colloidal silver, silver chloride, etc.), followed by physical development or else by alternately bathing the colloid stencil in a solution of a lead salt and in a sulphiding bath until sufficient density is obtained.(33) Since high resolution with stencil processes is only obtained if the colloid layer is very thin, the weight of black substance which needs to be deposited is likely to be high compared with the weight of the colloid layer. The mechanical resistance of such blackened stencils can only be low and they should generally be protected with a cover-glass.

(*iii*) *Stencils used as Resists to Etching*

Stencil images may be used as resists to protect a layer coated underneath them against the action of an etching bath or a " washing-out " solution. In some cases the resultant lines formed in the underlying layer itself serve as the graticule image, and the stencil then has to be a " positive " image so that only the lines of the design are protected against the etching action. Images of this type have been made from silver or lead-sulphide mirrors protected with a stencil formed from a bichromated colloid.(33) The underlying layer may alternatively be protected by a " negative " stencil, so that only the lines are eaten away and the resultant secondary stencil is used to protect the support itself against an etching treatment. This type of process was evolved because of the difficulty of producing a photosensitive layer thin enough to permit fine lines to be formed but yet resistant to the penetrating vapours of hydrofluoric acid, which is used to etch glass. Clearly such two-stage processes permit a much freer choice of substance for the final stencil. Silver-mirror stencils have been used widely as secondary stencils when etching glass. Loening (34) has described the production of " Bakelite " stencils protected with a bichromated gum-acacia stencil and washed out with lactic acid. His article contains an interesting discussion of the conditions needed for preventing local gaps in the stencil and for ensuring satisfactory washing-out of the fine lines. Cox and Hallam (35) used secondary stencils formed from bitumen and Canada balsam or bitumen and " Arochlor ". A benzene-grease mixture was used for washing-out the stencil and a hydrofluoric-acid solution containing glycerine was used to etch the glass.

(*iv*) *Stencils used to protect the Support against Deposition of Fresh Material*

Stencil images have also been used to protect the base material against the deposition of fresh material. Perhaps the most elegant method of this type is the application of metal vacuum-evaporation and sputtering by the B.S.I.R.A. in Great Britain (see page 196), and in the United States of America by R. D. Geiser of Messrs. W. and L. E. Gurley.(10) In this process the metal deposit covers the entire surface of the blank but is only deposited on the glass through the gaps in the stencil. The background can therefore be cleaned by dissolving the stencil away so that it brings with it the metal it has received. This method has the attraction that it can be used for the application of metals such as aluminium or platinum or rhodium, which it would be difficult to apply by any other method. It can also be used for application of non-metallic materials such as magnesium fluoride, and Guellich has proposed making the light-retarding discs used in phase-contrast microscopy in this way.(36)

In another variation of this method Gresham and Loening deposited metal electrolytically through a " Bakelite " stencil, which had been formed on a polished, nickel-plated copper plate.(37) After the stencil had been washed out, the nickel layer was for a short time made the anode in an electrolytic bath, " to passivate " the nickel and facilitate subsequent stripping of the image. The plate was then made the cathode in a copper-plating bath, and copper was deposited to a thickness of 0·0002–0·0004 in. (5–10 μ), so that the thickness of the metal layer never exceeded that of the stencil. As soon as the metal became thicker than the stencil, rapid spreading of the image occurred. The central portion of the image was then protected with bitumen varnish, and a further 0·003 in. (75 μ) of copper was plated around it to form an annular supporting ring strong enough for convenient handling. The stencil image was finally dissolved away, and the copper was stripped with a razor-blade, giving a copper disc of 0·4 in. (1 cm.) diameter, with a 0·2-in. (5-mm.) diameter opening covered with a mesh having 200 lines to the inch (*Figure* 68). Grids made by this method were first required for use in radio equipment and are now used as specimen-holders in electron microscopes. There seems no reason why the same technique should not be more widely used for making other small metal parts.

(*v*) *Complex Procedures*

Some procedures for producing graticules have been very complex, particularly when deposition of fresh material on top of a stencil image has been used to improve its resistance to a subsequent etching operation. Guellich described the production of graticules from a bichromate-shellac stencil on a silver mirror.(38) The mirror was etched out through the stencil, and aluminium followed by platinum or gold were applied by sputtering. The original shellac and the rest of the silver image was removed, leaving an aluminium stencil covered with a noble metal, and this was used as a resist for glass etching.

Gresham and Loening (19) made electrically-conducting images on film base by silver plating a cellulose-acetate base, forming a stencil image from a bichromated-glue layer on top of the silver, and etching the silver through the stencil with alcoholic ferric-nitrate solution. The electrical resistance of the silver film was too high for the final product, but its conductivity was sufficient to permit copper to be deposited electrolytically after the glue stencil had been removed. These images were used experimentally as strain gauges, being attached to some highly-stressed mechanical element such as an aircraft propeller, and indicating the strain by a rise in electrical resistance.

Where extreme robustness and only simple designs are required, graticules have been made by etching right through a thin copper

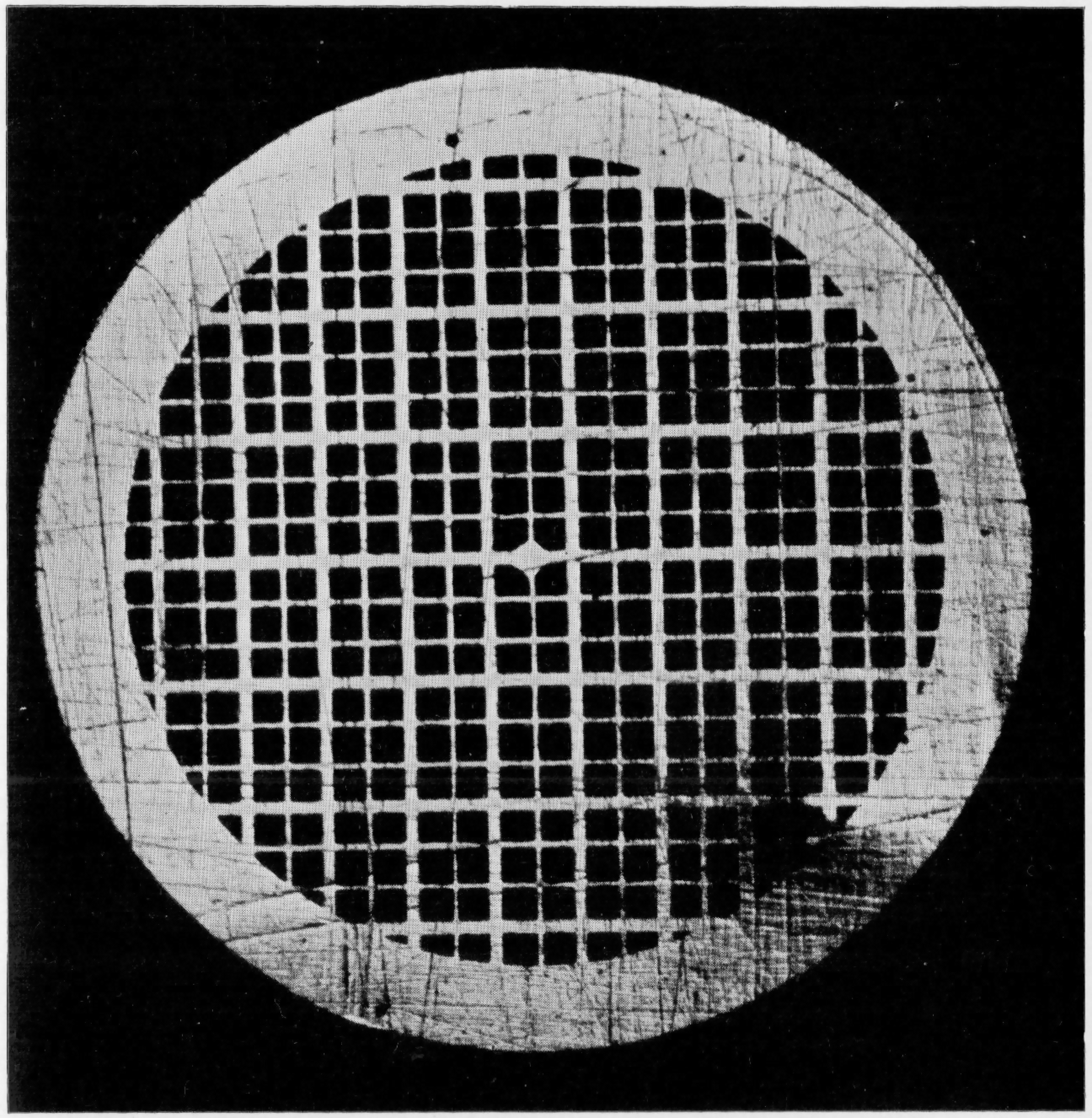

FIG. 68. *Electron-microscope Grid manufactured by Graticule Technique*

Photomicrograph (× 32) of grid used to support specimen in electron microscope. The grids are made by electro-deposition of copper through a stencil and subsequent stripping of resultant " image ".

sheet, so that the pattern is formed by the holes in the copper. In one application it was found that the copper had to be at least 0·012 in. (0·3 mm.) thick to give the stiffness needed, and serious under-cutting was certain to occur during etching, even if carried out from either side (*Figure* 69). A most elegant solution to this problem was found by Gresham,[39] who argued that some under-cutting did not matter so long as the correct line width was preserved at the very surface of the metal. His process used the following steps. A " Bakelite " stencil was formed on either side of the metal by exposing the coated plate between a pair of registered negatives, so that the stencils corresponded to the " lines " which were to be etched away. When the final graticules were used the eye would be focused on only one side of the aperture, and one of the negatives was therefore made with wider lines to allow for small registration

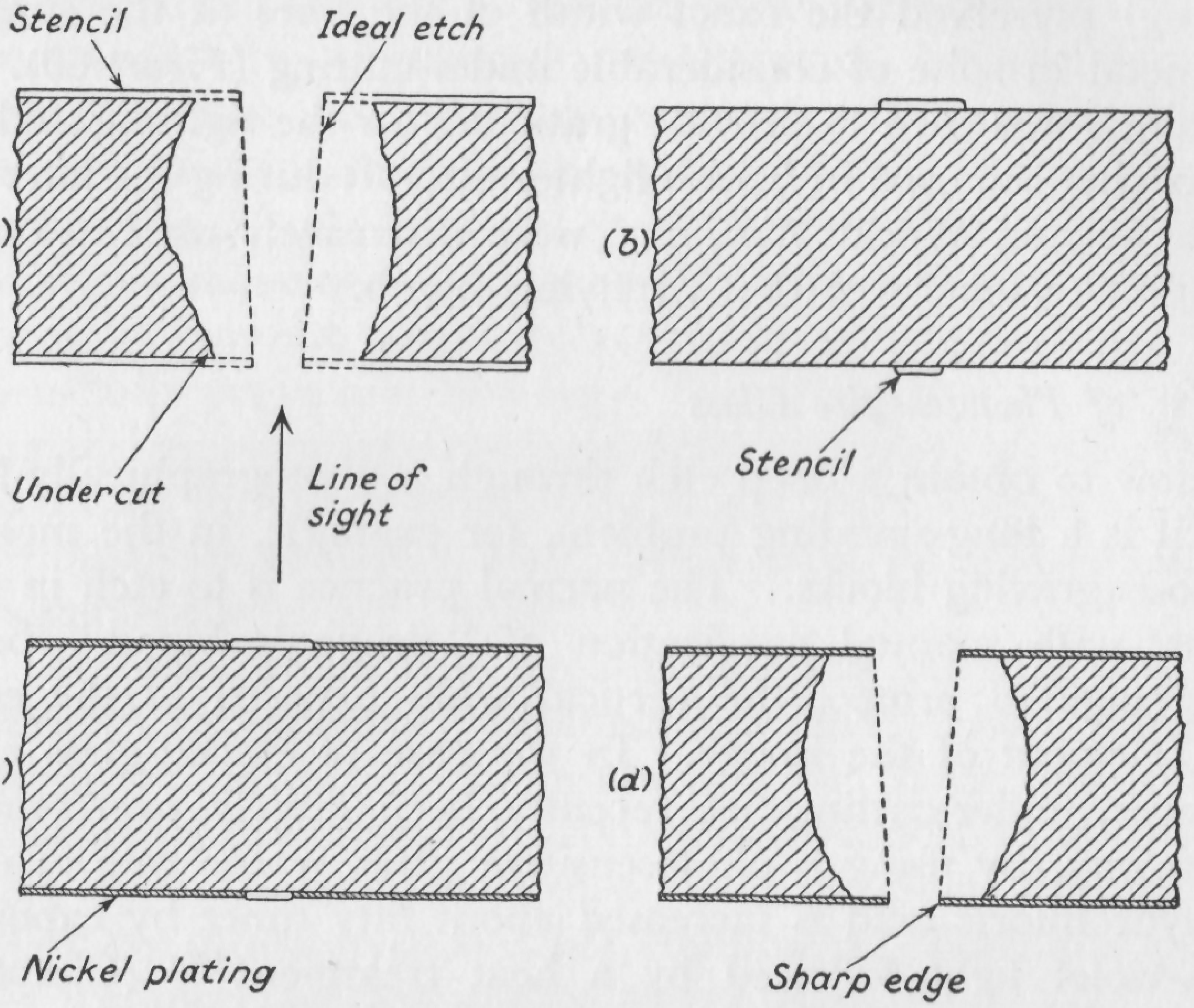

FIG. 69. *Correction of Under-cutting.*

(*a*) *Deep etch through negative stencil.* Serious under-cutting results from failure of stencil to protect metal surfaces uncovered by etching.
(*b*) *Application of positive glue stencil.*
(*c*) *Electrolytic formation of negative nickel stencil.*
(*d*) *Deep etch through nickel stencil.* Under-cutting still occurs, but edges of lines are now sharply defined by nickel stencil.

errors. The background on both sides of the metal was now electroplated to a thickness of 0·0005 in. (12 μ) with nickel. On removal of the " Bakelite " stencil the nickel layer now served two functions, since it not only acted as a resist during electrolytic etching of the copper, but also (by virtue of its resistance to the etching) preserved the exact width of the lines at the surface of the metal in spite of considerable under-cutting (*Figure* 69). This technique was used to provide graticules for the sighting and ranging mechanism used in British fighter aircraft during the later stages of the Second World War, and were extensively used in counteracting the menace of the V1 flying bomb.

Etching of Photosensitive Glass

How to obtain a deep etch through a photographically-formed stencil is a long-standing problem, for example, in the making of photo-engraving blocks. The normal practice is to etch in several stages, with manual application of " dragon's blood " between each stage to protect the vertical walls exposed at the edge of each element of the image. In the case of etched-glass articles, however, under-cutting has recently been largely overcome in a novel way, by using a photosensitive glass whose rate of etching by hydrofluoric acid is increased about fifty times by exposure to ultra-violet light followed by a heat treatment (40) (Chapter 3). The image-wise resistance to the etching does not, therefore, depend merely on a resistant stencil applied to the surface of the glass, but extends right through its thickness. It is interesting to consider how this property is likely to work out in practice. The 50 : 1 etching ratio between exposed and unexposed areas means that 0·0002-in. (5-μ) wide lines etched to a depth of 0·001 in. (25 μ) should be widened by only 0·00004 in. (1 μ) ;* or a 0·005-in. (125-μ) line etched from either side through glass 0·040 in. (1 mm.) thick would only be widened by 0·0016 in. (40 μ). In the latter case some roughening of the glass surface in the background might also be expected to occur. This process has been used to make holes as small as 0·001 in. (25 μ) through glass and for the experimental production of aperture plates for the R.C.A. system of colour television.

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* Sideways etching is presumed to occur at *both* edges of the line.

Organization of Graticule Production

The commercial-scale production of graticules introduces organizational problems, in addition to the technical problems already discussed. The working out of production routines and the layout of work-rooms and equipment in order to keep dust to a minimum merits careful thought. The use of air-conditioning and filtration, combined with electrostatic precipitation, are useful precautions, but blemishes are still likely to occur. It may also be desirable to use distilled water in the sprays of the air-conditioning plant (reference 22 of Chapter 12). Other obvious precautions are to minimize movement by arranging for each type of operation to be done in separate rooms connected by service hatches, and to use non-fluffy protective clothing. It is important to avoid aggravating the problem by disturbing deposits of dust which are relatively harmless in their settled condition. Dust troubles can increase seriously immediately after rooms have been cleaned, or when camera-bellows are moved.(41)

Another problem is the selection and training of operators to perform exceptionally exacting repetitive work. Inspection and spotting of graticules, for instance, is not particularly difficult, but imposes such strains that only a small proportion of candidates for this work are likely to prove suitable. Such difficulties can be eased by provision of suitable equipment. Binocular microscopes, for instance, are less trying to use than monocular instruments, and working comfort is further improved by using projection viewers whenever practicable for inspecting images.

The most detailed account yet published of the industrial production of graticules is the report on the Möller graticule factory, and readers intending to undertake graticule work are advised to consult this document, which contains many hints on organizational questions in addition to technical information.

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CHAPTER 12

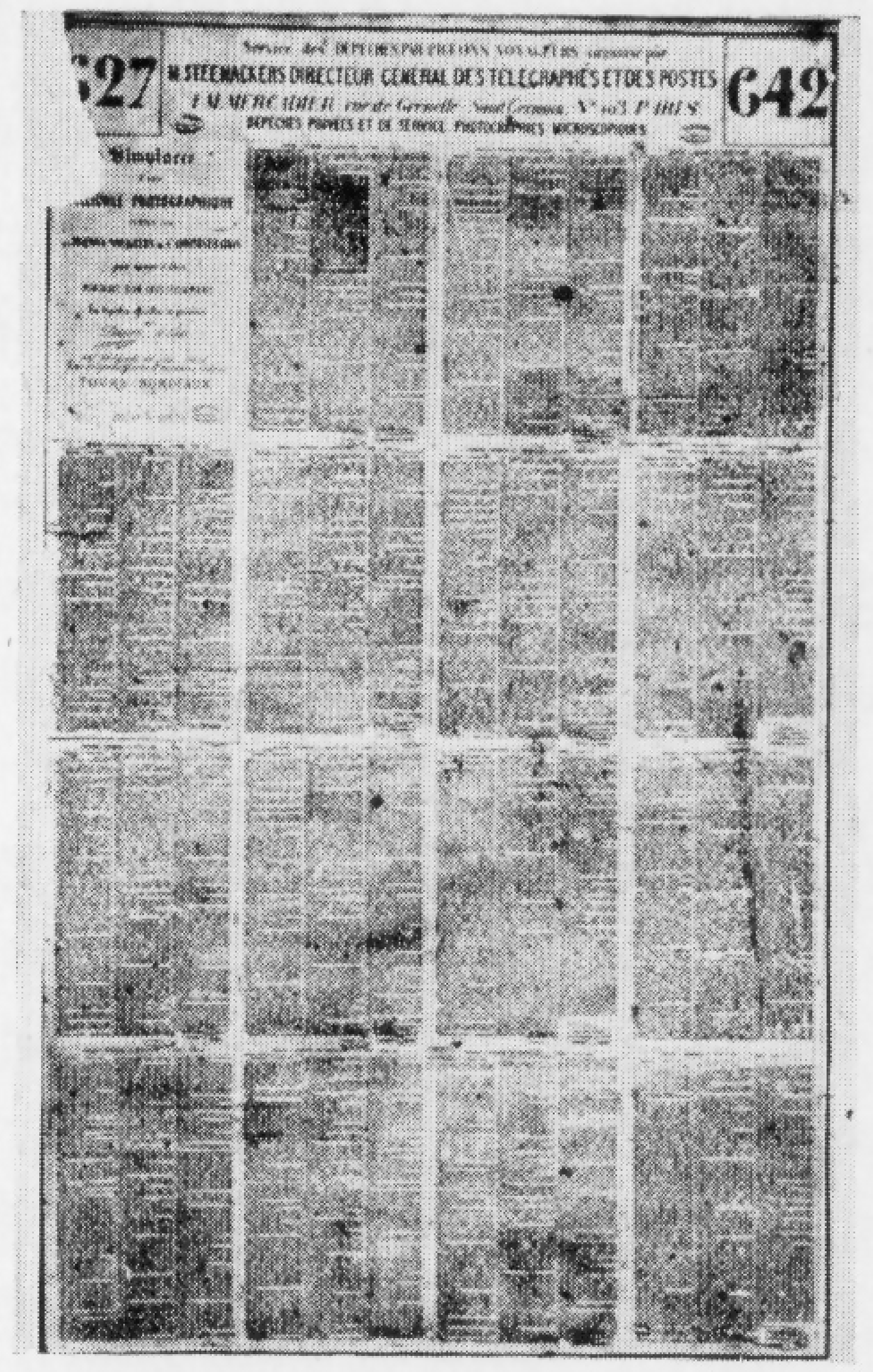
Document Microphotography

THE COPYING of documents on a reduced scale has attracted more public attention than all other forms of microphotography taken together. Indeed, for many readers, " Document Copying " and " Microphotography " are likely to be almost synonymous. Although many of the images produced by commercial processes can only just be described as " microscopic ", the present tendency is towards a further reduction in the size of document copies, to give images of more truly microscopic dimensions.

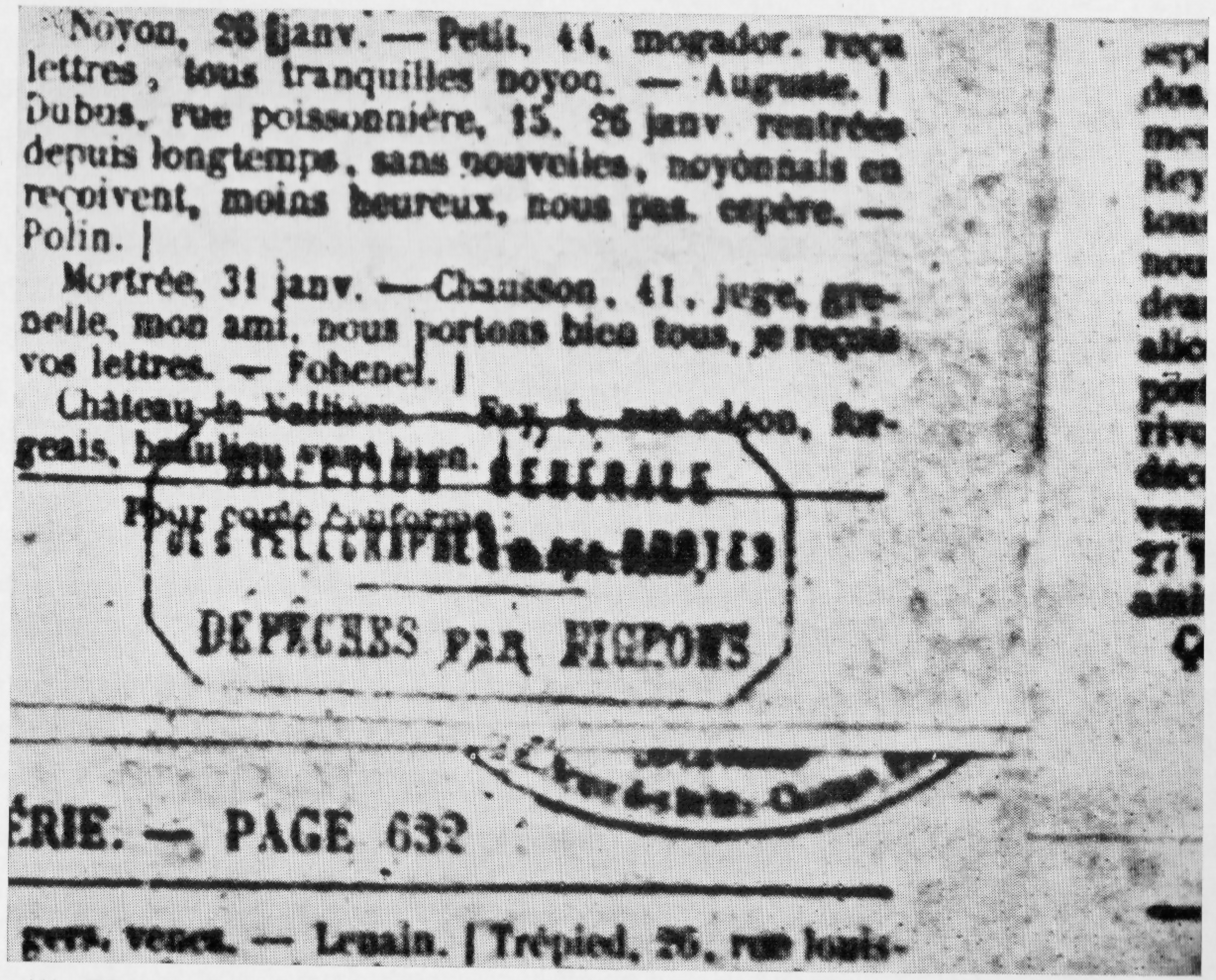
The idea of compressing information by the photographic reduction of documents is essentially simple, but historical, organizational and technical factors have all tended to complicate its practical realization. In a report of an investigation carried out for U.N.E.S.C.O., Verry noted that equipment, materials and operating techniques have been developed independently in different countries, producing a variety of processes for which neither sensitive materials nor reading instruments are conveniently interchangeable.(1) Even different groups of users in one country have different requirements, and it often happens that features invaluable for some applications have no advantage or may even be a nuisance for others. A number of processes are already (1956) commercially available, and modified systems are being evolved to suit the needs of various users. In spite of this, many questions about the use of document microphotography have not yet been finally resolved. In view of these complications it seemed that the space available in this volume would be sufficient for no more than a review of the subject. The main purpose of this chapter, therefore, is to provide an introduction for further study.

Historical Notes

It has been shown in Chapter 1 that the making of miniature inscriptions has been practised for many centuries, and that Dancer



(*a*) Reproduction (actual size) of pellicle made by Dagron in 1871.



Noyon, 26 janv. — Petit, 44, mogador. reçu lettres, tous tranquilles noyon. — Auguste. | Dubos, rue poissonnière, 15. 26 janv. rentrées depuis longtemps, sans nouvelles, noyonnais en reçoivent, moins heureux, nous pas. espère. — Polin. |

Mortrée, 31 janv. — Chausson, 41, jeûne, grenelle, mon ami, nous portons bien tous, je reçois vos lettres. — Fohenel. |

Château-la-Vallière. — [illegible], rue odéon, forgeais, [illegible] bien.

Pour copie conforme :

DIRECTION GÉNÉRALE DES TÉLÉGRAPHES [illegible]

DÉPÊCHES PAR PIGEONS

ÉRIE. — PAGE 632

gers, venez. — Lenain. | Trépied, 26, rue louis-

(*b*) Photomicrograph (×40) at intersection of pages. In addition to a readily legible image, print shows edges of sheets and partial covering of official stamp, proving that many printed sheets were copied with a single exposure.

From the Kodak Museum, Harrow.

FIG. 70. *Image borne by a Dagron Pellicle.*

[*Facing p. 233.*

first produced his microscopically-reduced photographs more than a century ago. Contemporary scholars soon realized the potentialities of Dancer's method for the compression of information. Thus in 1853, the astronomer Sir J. Herschel⁽²⁾ proposed the making and publishing of microphotographic reproductions of reference books, and in 1857 Sir D. Brewster pointed out that dispatches or secret information could be concealed in a space not larger than a full stop or a small blot of ink.⁽³⁾

These and other descriptions from the same period leave no doubt that the basic problems of making quite legible images of truly microscopic proportions had, by that time, already been solved ; but little use was made of these suggestions for over sixty years. One notable exception was the Pigeon Post operated by Dagron in 1870–71 for sending messages into Paris during the Franco-Prussian War.⁽⁴⁾ The cables under the Seine were cut, and the besieged city was completely isolated from the rest of France. The postal service was operated by printing the official dispatches and civilian messages in bold letters on folio pages, which contained as much information as a large newspaper page. Sixteen such pages were mounted on a panel, and were reduced by a single exposure to give an image measuring only $2\frac{1}{2} \times 1\frac{1}{2}$ in. (65 × 35 mm.) (see *Figure* 70). The resulting negatives were contact printed on collodion plates, from which the processed emulsion was stripped as a coherent pellicle. Each pellicle contained about 3,000 messages, but they were so light that 18 only weighed 8 grains (0·5 grams), and this number was carried by a single pigeon in a quill attached to a tail feather.⁽⁵⁾ On receipt, the films were projected by a lantern and the messages copied by hand. The military value of this successful process was considered to be so high that full working details never appear to have been released for publication.⁽⁶⁾ Collection of information from the literature of that period and examination of surviving specimens of Dagron's pellicles have, nevertheless, permitted a reasonable reconstruction of his methods to be made.⁽⁷⁾

Several reasons can be suggested for the slow adoption of the early proposal for applying document microphotography to practical problems. The production of the first satisfactory specimen images demonstrated the *potentiality* of the process for document copying, rather than its *immediate practicability*. Large-scale use demands that cheap and reliable methods must be evolved for making very large numbers of images. In this connection it should be noted that important ancillary goods, such as transparent and flexible film base, and convenient illuminants for reading machines, were not developed until much later. The absence of such materials may well have retarded the development of document-copying processes. It also seems probable that the demand for document microphotography in 1860 was not sufficiently pressing to stimulate the necessary development work. Many years were needed to bring us to our present condition, where the need for such processes is only too painfully apparent. Since then, science has taken enormous strides ; discoveries have stimulated whole groups of further discoveries, and this process has been accompanied by a comparable expansion of industry and commerce. With this expansion there has been a tendency for all human activities to be concentrated into larger and larger working units. The value of records thus increased greatly, as did the financial loss which would result from their destruction. Document microphotography has proved to be a valuable safeguard, since once the documents have been copied, further copies can be made simply and more cheaply ; and the smaller space occupied by the copies means that storage is at the same time more secure, more convenient and cheaper.

The expansion of science and technology also caused libraries to grow, and those housing bound copies of journals and newspapers were faced with the expense of storing many large and heavy volumes. In many such cases microphotography has enabled the librarian to remove the originals from the shelves and yet to provide a wider range of journals than would otherwise have been available. The period since 1860 has also produced profound changes in the working environment of the scientist and scholar. A century ago one man could comprehend a fair proportion of the existing knowledge of the material world, but in 1956 he can no longer hope to grasp more than a small fraction of the knowledge existing when he was born. He cannot even keep up to date, for it has been estimated that a hundred years would be needed to read all the scientific papers now published in a single year. The scholar is therefore faced with the problem of finding the information relevant to his field of study. Microphotography is proving useful both in making

rare works available, and by providing the information in a form which can be scanned by automatic searching systems. Microphotography will obviously also help to relieve the " famine " to be expected from the continuous expansion in the world's consumption of paper.

In short, document microphotography is now a necessity, and activities of great social value would be seriously hampered without its aid. It has been truly stated that there are many purposes for which microphotography is not only acceptable, but is also particularly suited. For some purposes there is no adequate alternative.

The Demand

Before considering the technical aspects of document-copying processes, it will be convenient to examine the various ways in which different groups of users employ the copies, and the different features of the process which are of critical importance to them.

The known applications of document microphotography can be grouped into five classes :

1. Administrative work,
2. Preservation of records and archives,
3. Intellectual and scientific, including the publication of " short runs ",
4. Collection, classification and finding of information,
5. Transport of information.

Although some of the requirements of all the groups will be similar, the first two have tended to use document microphotographs in a rather special way. The administrative workers have largely used them as an insurance against accidental loss. When this is done there is a good chance that the copies may never have to be read, or will only be read very occasionally. The convenience of storage has therefore been emphasized more than the accessibility of any particular document. In some administrative uses, such as the " Recordak " Single Posting System and the System of Accounting in Retail Stores, all the copies are, however, read. In the other groups, and particularly for intellectual work, the ease of finding specific references is considered to be more important, so that a system giving better accessibility may be adopted, even if it requires more space for the storage of the copies.

1. *Administrative Work*

The first full-scale administrative application was inspired by a New York banker (George L. McCarthy, first President of the Recordak Corporation), and led to the " Recordak " machines for making a record of every cheque which passes through a bank.(8) These had to handle very large numbers of originals every day of the working week, and gave a single copy from each original, although further copies could be made if needed. The process had above everything else to be utterly reliable. In general, each document was only likely to be subjected to a brief inspection (if it were read at all) and a *legible* copy (but not necessarily a perfect image) was all that was needed (see *Figure* 1). The same type of process can be used for making records of transactions by such units as *government departments, local government authorities, insurance companies, commercial houses and hospitals.* In this type of application the most important advantages are the security against loss or damage, complete elimination of copying errors and typing mistakes, insurance against frauds (particularly in football pools), and the small space within which the information can be stored.

If judged by the amount of equipment and film used, the application of " microfilm " to administrative work is more important than all the other applications taken together. It has been estimated that in the United States of America more than 99 per cent. of microfilm is used for administrative purposes. It is not improbable, however, that the application to intellectual and scientific work may ultimately prove to be the more important, when judged by its influence on the history of the human race.

2. *Preservation of Records and Archives*

Document copies used for administrative work usually need to be stored for only a relatively brief period, and are likely to be of little further use after ten or twenty years. Microphotography can also be used for the permanent preservation of records and archives against destruction for many decades, or even for centuries. Records on rolls of film have a special suitability for this purpose, since they permit subsequent copies to be made cheaply and rapidly when the first copy shows any signs of deterioration. They can thus be used to preserve the inscriptions long after the original documents have distintegrated or have been destroyed, and the people concerned with their production are all dead.

Microphotographs for the preservation of records should be made with special care, and the American Standards Association has laid down specifications for such permanent records.(9) The film base should be of the " safety " type and not contain more than a small proportion of cellulose nitrate. It should show only small changes of flexibility, pH and viscosity of a solution of the base after ageing for 72 hours at 100° C. The film should also be processed so that the residual hypo content is less than 0·005 milligrams per square inch, and neither intensification nor reduction of the developed image is permitted. While these recommendations are generally adequate, there are two further precautions that might be added when the copies have to be stored in a tropical climate. In the first place, gelatin is prone to bacterial or fungal attack, particularly if stored at a high humidity, and this can be hindered by impregnating with a fungicide solution just before drying. In addition, the finely divided silver of a photographic image may in some circumstances fade, but can be stabilized by sulphur, selenium or gold toning. It should finally be noted that a photographic archive, may, in the future, constitute the only surviving copy of a valuable document. The highest possible standard of reproduction is thus to be desired. The whole subject of preserving photographic records is discussed in an Eastman Kodak pamphlet.(10)

3. *Intellectual and Scientific Work*

The dissemination of information connected with the learned professions is a field in which document microphotography is already being used, and in which its applications are likely to expand greatly. It is apparent that document microphotography will affect every link in the distributive chain between author and reader. *Authors* whose writings can only have a limited circulation will welcome the opportunity which microphotography offers for the cheap and rapid publication of limited editions. In the United States of America, for instance, an increasing number of doctoral theses are being published in this form. Publication by microphotography is also valuable when normal printing methods would be impossibly expensive, as in the reproduction of work containing long tables of figures. Authors should also not forget the benefit they derive from studying the work of others, and hence from the greater accessibility of information obtained by the use of microphotography. In other respects, however, authors might suspect that the wide-spread production and circulation of photographic copies by librarians could reduce their income from royalties. *Publishers and editors of learned journals* may also fear a loss of revenue when numerous readers obtain microphotographic copies, rather than the original journal. This may be particularly serious for some learned societies, which derive a substantial proportion of their income from the sale of " back numbers ".

The *librarian* represents the most highly stressed link in this distributive chain, since he must try to make available both the current and out-of-print works required by his readers, in spite of limited space and money. It is, in fact, the librarians who are most immediately affected by the enormous volume of current publications, and much of the stimulus for the application of microphotography in this field has come from them. Microphotography offers an economical means for satisfying the demand for seldom-wanted journals or books or individual articles, for filling gaps in runs of journals (particularly gaps caused by the two World Wars), and for building up a file of copies of articles dealing with specialized fields of knowledge. It allows all these aims to be achieved with a saving of space and the security derived from the readiness with which further copies can be made. Document microphotography also allows loans of information to be made available while the original source, books or journals are still available for reference on the shelf. It has, moreover, been pointed out that the cost of making and sending a microcopy of a paper for a reader to keep may be less than the administrative and postal costs of loaning the journal itself.

The librarian is likely to be concerned with requirements of only secondary consequence to other users. The question of durability and permanence and maintenance of legibility after repeated handling is clearly important, so is that of keeping the documents in a definite sequence in spite of the worst efforts of readers to mix the copies up.

The reader may feel the need for microcopies at any time in his career. During the earlier stages of his studies, the high price of books is likely to prove at least as noticeable as the mere lack of availability. When he was later to consult original papers, he will realize that many works are none too accessible. Only too often it seems that the papers most eagerly sought are in unobtainable volumes, almost as if they were deliberately hiding. In spite of this, most academic workers are not enthusiastic about using microcopies for their studies. This dislike can be partly ascribed to habit. From the start of their school days, scholars are taught to use bound books. They develop special skills in the use of these (such as the rapid finding of any desired page) and learn to like the feel and sight and smell of books. With microphotographs, a machine has to be used to make the text readable and to find the pages, and the reader is forced to form a new set of reading habits. Although such objections are relatively trivial, they might have a profound influence on the attitude of some scholars. There are, however, more tangible objections. The subject-matter of an original paper can be far from easy to grasp, even when written in the scholar's mother tongue. The scholar will therefore often have to peruse a document in the greatest possible detail, and may even wish to take measurements from curves illustrating experimental data, so that calculations or deductions can be checked. In short, intellectual or scientific papers must frequently be studied more intensely than administrative papers, and should correspondingly be copied so as to give a higher standard of legibility. Acceptance of poor copying standards for the sake of cheapness is only likely to delay the wider acceptance of these aids to learning.

Some difficulty has been caused by the size of the units which the scholar needs to handle. This is particularly true with respect to reprints of original papers, which often contain only 10 or 12 pages. Roll film can, of course, be cut into the lengths required, but this immediately introduces the problem of filing. The microcard (see below) can also be used, but the type capable of recording 50 or more pages will be wasteful, since only a small proportion of the space will often be used.

4. *Collection, Classification and Finding of Information*

Microcopying processes can also be used to collect and to assist in the classification and finding of information. The use of narrow-gauge ciné cameras for recording dial readings in power stations, aircraft and racing cars is closely related to document microphotography, although it is more conveniently regarded as an application of cinematography. This field can also be extended to include the recording of results from computing machines, or to recording instrument readings in circumstances too hazardous for a human observer. Microcopying processes can also be adapted to the assembling of indexes and information files. Holmstrom has described how Recordak copying was used by Imperial Chemical Industries to build a Master Index so that information beyond the scope of the firm's specialized libraries could be distributed to each of its eleven manufacturing divisions.(11) On one 3-in. (75-mm.) length of film was recorded the subject-matter code according to the Universal Decimal Classification, and a serial number (both legible to the naked eye), a reduced copy of the page of the abstract journal and the following page. The lengths of film were filed in pockets on 5 × 3 in. (125 × 75 mm.) index cards.

Document microcopying can be used in conjunction with machines for selecting information of a specific kind from entries in a large filing system. Thus copies of abstracts or even of complete articles can be attached to the cards of a machine such as the " Hollerith ", which selects cards on the subject required by operation of a coding system using punched holes. This development has been undertaken by the " Film N File " Corporation of New York. The same type of result will be achieved more rapidly by the Rapid Selector project initiated by Vannevar Bush at the Library of the U.S. Department of Agriculture.(12) Each frame of the microfilm contains an abstract and a reference code consisting of an area of black film with a system of clear spots. The film is moved rapidly past a projector, which causes the image of the spots to be superimposed on an " interrogating card " bearing black spots on a white ground, corresponding to the subject-matter for which references are sought. The combined images are scanned photo-electrically, and when the two patterns coincide, an electronic circuit causes the images of the desired frames to be printed on an unexposed film by means of an electronic flash. The first prototype scanned film at the rate of 72,000 frames per minute, but an improved version is being designed which will search at 120,000 frames per minute. It has also been suggested that similar results might be obtained by printing a sound track on the side of the film and using a code of musical notes to extract the information required. The possible value of such machines will be obvious to all scholars who have spent only too many hours searching the indexes of abstract journals.

An entirely different method for collecting information on microfilms has been evolved by the Diebold Corporation in the United States, under the name of " Cumulative Microfilm ".(13) A transparent sheet 8 × 5 in. (20 × 12·5 cm.) is used with a cement which allows roll films to be cut and stuck to the sheet. This method permits individual records to be assembled into one unit, and additions or withdrawals are made as desired. Cumulative Microfilm was designed chiefly for hospital records, to allow all case records, irrespective of the number of admissions, to be retained on one unit sheet. The sheets are stored in envelopes and filed in a cabinet, and a special reader has been developed for viewing them.

5. *The Transport of Information*

The small weight and volume occupied by the information on document microphotographs is obviously of advantage for transport from place to place, and we have already noted the use made of this property by Dagron during the siege of Paris. Renewed interest in the use of microphotography for war-time postal services was shown during the Second World War, and most men in the Allied forces serving overseas were grateful for the facilities offered by the " Airgraph " and " V-mail " services. The letters for these had to be written on special sheets, and were reduced on 16-mm. films (*Figure* 72), which were developed and sent by air to the distant distributing station.(14) On receipt, each letter was printed in an enlarger employing a continuously-moving band of sensitized paper (see below), which was linked to a continuous-processing machine. The paper was finally dried on a hot drum, and cut into individual letters. The same system was also used for transmitting confidential Government or military information. At the peak of their use these services handled a million letters a day, but the mechanization and organization needed is so large that they are only economic when the demand is correspondingly great. It is doubtful whether the peace-time demand will prove sufficient to justify the continued use of this method. There is, however, still a real need for a microphotographic system to transmit information to workers in learned professions in countries with less adequate library facilities. The information possessed by the isolated worker in a jungle or polar region need to-day only be a week or two behind that of his colleagues working in a city.

One can also envisage circumstances in which travellers will wish to carry information in a greatly reduced space. Road maps are a possible application, where a large scale is needed to permit a driver to find his way through towns, but would make the size of the maps prohibitive for any but a very short journey. Microphotography might be used to provide maps, nautical almanacs and other useful information in ships' lifeboats or rescue dinghies for aviators. It has been stated that the drawings for an average warship weigh 10–12 tons, and their storage and transport to permit repairs to be carried out has been assisted by reduction on microfilm. Microphotographic books are also likely to prove an essential adjunct of inter-planetary travel.

Coupled with the small weight and volume of truly microscopic document copies is the ease with which they can be hidden, and it is not surprising that they have been employed in espionage. The most striking case is that described by J. E. Hoover of the United States Federal Bureau of Investigation.(15) It was found that the Nazis were hiding microphotographs of espionage documents in the full stops of printed papers and telegram forms. The microscopic images on film were cut out with a hypodermic needle and inserted between the paper fibres. Sir David Brewster's ninety-year-old prediction (3) had been literally fulfilled.

Organizational Problems

Although the basic principles of document microphotography are essentially simple, the problem of meeting the main requirements of most important users is quite complex. The specifications of existing or possible processes can vary in many important ways. The final copies can be made on film or paper. Film is more likely to show damage on repeated use, since it has two polished surfaces which show scratches readily, whereas a moderate degree of scratching of the surface of an unglazed print is unlikely to be readily noticed. The base material also influences the storage of the developed images, since it is more difficult to wash the residual hypo from paper and the images may be more liable to fade. The

images can be arranged in various ways to fill the area of the film. Thus, with either 35-mm. or 16-mm. film, one image can occupy the space of two ciné frames, or one or two images can occupy the space of a single frame. The images can alternatively be placed in rows and columns to fill the area of a rectangular sheet (*Figure* 2). As will be seen later in this chapter, radically different mechanisms are needed for making the copies (and for finding the pages when reading) in the roll-film and sheet-film processes, which also tend to appeal to different groups of users.

Practically all the images produced so far are black-and-white, but there is a suggestion that coloured images will be useful when copying such originals as illuminated manuscripts or medical illustrations. The image quality required can be fixed either at the level of tolerable legibility or may be designed for prolonged study, and this choice controls the greatest degree of reduction which can be used. In addition some processes may only be required to copy good-quality documents, whereas others may have to cope with poor originals such as weak carbon copies. An important auxiliary feature is the means used for identifying or finding the microcopies. In some systems special provision is made for copying bibliographical information at a scale which allows it to be read by the naked eye. This can be arranged very conveniently with sheet microfilm or microcards.

It is clear that many different systems could be devised by varying these specifications, and certain features of each system will suit some types of users and be inconvenient for others. The most economical aim would be to devise the smallest number of systems giving a tolerably convenient service to all users. The necessary inquiries might form the basis for a programme of operational research, but in the meantime much is being done empirically by the use and modification of existing processes. This method not only teaches the producer how to satisfy the users but also allows the " customers " to learn what features they should demand of the producers or manufacturers.

Verry has made interesting proposals for improving the present lack of order and interchangeability of microcopying methods.(13) In Europe particularly, it appears that the application of microphotography has been hindered by the diversity of apparatus and processes used, and neither manufacturers nor users are inclined to develop equipment further or extend its use until some measure of standardization, particularly with respect to image sizes, has been introduced. Standardization will not be an easy task but might be assisted through the leadership of an organization such as U.N.E.S.C.O. A universal reader capable of dealing with most forms of document microphotographs would also be useful. Other definite proposals he makes are:

1. That a directory of microphotographic materials and apparatus should be published (this is now being done),$^{(16a)}$
2. that a standard book of instruction on microphotographic technique, illustrated by results of good and bad procedure, should be published in several languages,
3. that a test chart should be designed for assessing the quality of microfilm, as recommended by the technical committee of the International Standards Organization.$^{(16b)}$

Legal Problems

In addition to specifying the requirements for any particular use, operators of document-copying processes should ascertain any legal restrictions on their work. The copying of bank-notes and coins is generally a criminal offence, although it is doubtful whether convincing forgeries could be produced by enlarging a microfilm negative! In Great Britain, this prohibition appears to apply to deliberate copying but not, for instance, to cases where the notes form an incidental part of the photograph. The ruling in the United States of America is much stricter, so that a photograph showing the handing of a bank-note to the winner of a competition is, for instance, forbidden. The photographic copying of many other documents such as Government bonds, postage stamps, automobile licences and naturalization papers is also illegal.$^{(17)}$

A more generally troublesome restriction is the danger of prosecution for the infringement of copyright. Messrs. Bristows, Cooke and Carpmael point out that copyright is a form of property which consists of the sole right to reproduce a literary work, and is valid for fifty years after the initial publication.$^{(18)}$ The only relevant exception in the British Copyright Act is that infringement is not constituted by " any fair dealing with any work for the purpose of private study, research, criticism, reviews or newspaper summary ". These authorities consider that making a microfilm of a copyright publication would be an infringement, as would be the making of further copies or even the projection of the image on a screen.

Now, in the Proceedings of the Royal Society Scientific Information Conference it is stated that:$^{(19)}$

" Science rests upon its published records, and ready access to public, scientific and technical information is a fundamental need of scientists everywhere. All bars which prevent access to scientific and technical publications hinder the progress of science and should be removed. Making single copies of extracts from books or periodicals is essential to research workers and the production of such single-extract copies by, or on behalf of scientists is necessary for scientific practice."

Although the protection offered to authors and publishers by the Copyright Act has certainly stimulated publication, it would seem to be a potential source for a conflict of interest between them and the community at large. The " fair-dealing " clause appears to offer a loophole to the would-be copier, but Messrs. Bristows, Cooke and Carpmael point out that the courts have not (and probably would not) laid down any rule defining " fair dealing ", and are likely to examine each case on its merits. This could well mean that production of photocopies would be practically halted, if the majority of learned societies decided to prosecute for infringement of copyright every time one of their publications was copied. In fact, such a situation is unlikely to occur, since scientific societies are themselves part of the scientific community, and it may be regarded as axiomatic that neither they nor their members wish to place any obstacle in the way of disseminating scientific knowledge. On this basis of good-will, the Information Services Committee of the Royal Society of London drew up a " Declaration on Fair Dealing in regard to Copying ".$^{(20)}$ Societies subscribing to this would state that they did not object to the making of single copies of parts of their publications under certain limited conditions. These conditions contained a number of safeguards for the copyright owners and were based on those previously drawn up by the National Association of Book Publishers of the United States of America. The most important part of the " Fair-Dealing " Declaration reads as follows:

> We will regard it as fair dealing for the purpose of private study or research when a non-profit making organization such as a library, archives office, museum or information office, owning or handling scientific or technical periodicals published by us, makes and delivers a *single* reproduction of a part of an issue thereof to a person or his agent representing in writing that he desires such reproduction in lieu of a loan or manual transcription, and that he requires it solely for the purpose of private study, research, criticism or review, and that he undertakes not to sell or reproduce for publication the copy supplied, provided that :
>
> (i) the recipient of the copy is given notice that he is liable for infringement of copyright by misuse of the copy, and that it is illegal to use the copy for any further reproduction,
> (ii) the organization making and furnishing the copy does so without profit to itself,
> (iii) proper acknowledgement is given to the publication from which the copy is made,
> (iv) not more than one copy of any one excerpt shall be furnished to any one person.

The exemption extends also to the officers of the libraries or organization, but involves the responsibility for ensuring that their employees caution those receiving the copies against misuse. The Declaration concludes :

> We reserve the right to take action against any person or organization copying or misusing a part or the whole of the work. We reserve the right to withdraw this Declaration.

The original subscription was for a trial period of two years. The invitation to subscribe was published in *Nature* on 13th August, 1949, and by November 24th, 101 (mainly British) societies had signed the Declaration.

While the Fair-Dealing Declaration does much to remove an obstacle to the wider use of document microphotography, neither the author nor the publisher lose any rights conferred by the Copyright Act, nor will the Declaration prevent them from taking legal action against an offender.

In conclusion, the reader should remember that the possible occurrence of infringement of the copyright of maps is carefully watched. H.M. Ordnance Survey, for instance, demand that permission in writing be obtained in every case before reproduction of their maps. It seems less likely that a plea of " fair dealing " could be applied for infringement of a map, and this does not seem unreasonable in view of the labour involved in their preparation.

Technical Problems

The production of a few tolerable document copies of the dimensions used in commercial practice is not particularly difficult and can be carried out by an amateur reasonably skilled in the use of a 35-mm. " miniature " camera. Many of the commercially-operated systems have so far only employed moderate degrees of reduction, so that some authorities have suggested that the images are not truly microscopic, and that it is absurd to call them " microphotographs ". With moderate degrees of reduction, the extreme precautions needed for securing exact focus when making much smaller images (Chapters 6 and 9) are no longer essential.

Commercial-scale operation, however, involves the production of immense numbers of images, each of a different page or document. It is obviously inconvenient (and probably also costly) to inspect every single image after processing, and retake those found to be faulty. In such circumstances the question of reliability is of paramount importance, and the average standard of reproduction should be so high that the checking and re-taking of images is reduced to a minimum. A high average quality is ensured by choosing operating conditions providing the largest possible working tolerances, and this is the principle around which successful operation must revolve.

Degree of Reduction

Although the basic aim of document microphotography is to compress information into a small space, various factors limit the degree of reduction which can usefully be employed. One should first note that the higher the degree of reduction demanded, the higher will be the required emulsion resolution, and the lower will be its speed (Chapter 3). Such a change is not altogether advantageous, since a high emulsion speed may add to the working tolerances by permitting the use of smaller lens apertures with greater depth of field, or the use of the shorter exposure times required for rapid working. These advantages are lost when a slower emulsion has to be used to secure a greater degree of reduction. With high degrees of reduction, moreover, accidental flaws and blemishes become increasingly dangerous and are important factors limiting the wider application of truly microscopic document copies, or so-called " ultra-microphotographs ". In addition, the smaller the images, the greater will be the number recorded on one unit of sensitive material, and the greater will be the effort wasted if even one image in any unit is spoilt by a blemish. The equipment required both for producing and reading highly reduced images has also to be made with greater precision, and is likely to be more costly. The design of reading equipment becomes especially difficult, since the total amount of light needed on the screen to ensure adequate legibility of a document is independent of the size of the microphotographic copy. The use of smaller images means that the same radiant energy has to be concentrated into a smaller area, and the danger of damage from over-heating becomes increasingly serious.

In spite of technical refinements used to prevent a loss of quality, the chance of the legibility of the images suffering increases with the degree of reduction employed. Designers of document-copying processes should, therefore, not overlook the user's point of view, which has been described by Verry.(13) The user reads microfilm by necessity and not by choice (i.e. because the original document is not conveniently accessible), and is rarely interested in technical achievement for its own sake. He therefore judges the value of microfilm by his ability to read it without strain ; and a given space containing 25 readily legible pages is preferable to 100 pages which can only be read with difficulty.

Arguments such as these force one to conclude that a document-copying process should be operated with the largest-sized images consistent with the designed aims of the process. In this connection, it might be noted that it is only too easy for a salesman to argue that a process reducing 100 cubic feet of documents down to half a cubic foot is twice as good as one reducing the same matter down to 1 cubic foot. The user would, however, be wise to ascertain whether the extra compression is really worth a possible reduction in image quality, and the probability that a higher proportion of images are likely to be unsatisfactory. He should also satisfy himself that the investment and over-all operating cost—not merely the price of the film consumed—really is lower when smaller images are used.

The Properties of Original Documents

The ease or difficulty of producing legible copies is greatly influenced by the properties of original documents. The nature of the inscription itself affects the result. Thus somewhat different exposure levels are needed to give the best possible rendering of

letterpress types of different size. When types of different size are used on one page, it is advisable to adjust the exposure to suit the smallest type face, since the legibility of this will suffer most from any errors of exposure. By contrast, typescript letters do not vary greatly in size but certainly vary greatly in clarity, blackness and density. Attempts to improve legibility of the weaker typescript documents by increasing the image contrast may actually lower the legibility by exaggerating the differences between the records of weak and strong letters.

The necessity for reproducing carbon copies of documents can seriously lower the working tolerances, since these may be on a coloured paper and can show great variations in the sharpness of the edges of the letters as well as their blackness. If a bad carbon copy is used as the original, any further degradation introduced by the photographic copying may make the image quite illegible.

The copying of hand-written documents is also not easy, since the writing of different authors may vary with respect to size, line thickness, spacing of lines and words and the actual blackness of the ink used. The difficulty is likely to become acute when pencil-written documents also have to be copied (see below).

Image Quality Required

The working tolerances will, in addition, be influenced by the faithfulness with which the copies are required to reproduce the sharpness of the original letters. One should remember that any photographic-copying process causes some degradation of image sharpness. This degradation may consist of slight rounding of corners or alterations of relative line widths which are only detected by microscopic examination. At the other extreme, it may cause the copy to be quite illegible. It is possible to set up subjective standards such as the following (see also Binkley (21)).

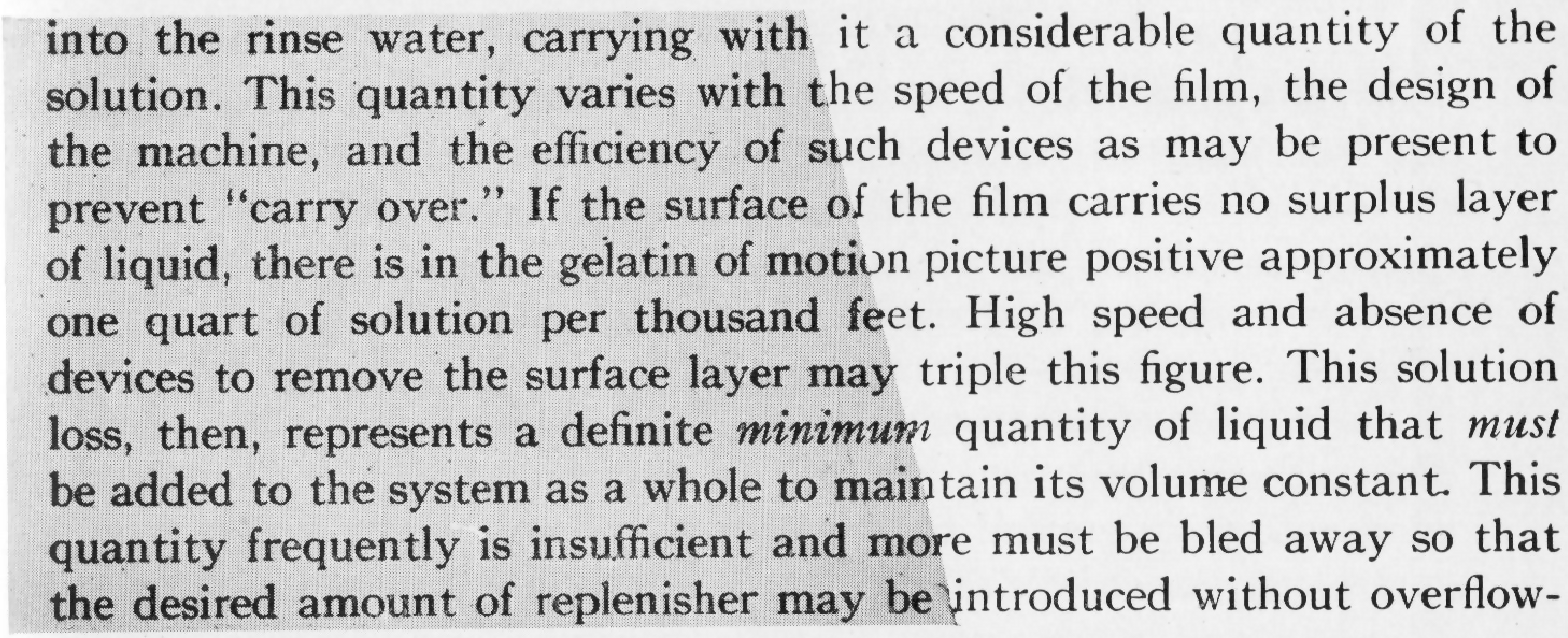
Standard	*Description of Copy*
Perfect	Degradation only just detectable. Copy suitable for students of printing.
Excellent	Degradation in no way affecting legibility. Copies suitable for prolonged study by scholars or research workers.
" Commercial " quality	Degradation obvious but copies still easily legible without eye-strain.
Decipherable	Degradation pronounced. Identity of individual letters doubtful. Words can be mostly read but some have to be guessed from the context.

When other factors, such as apparatus and degree of reduction, are held constant, the working tolerances will be greater the lower the standard of quality demanded. It can be suggested that " commercial " quality is the lowest standard which should be set for administrative use, and " excellent " should be demanded for scholarly purposes.

The level of contrast with which the process is operated will also influence the working tolerance. A process giving only a moderate photographic contrast will have greater exposure latitude, and hence easier working tolerances, than a high-contrast process. The opinions of the copier and the eventual user of the document copy can differ over this issue. There is a natural tendency for the user of any document-copying process to judge results by the appearance of the final copies, without making allowance for the properties of the original documents. Thus the copies may be required to have a black line on a white background, whatever the quality of the original. With many documents, particularly if typed or hand-written, this result can only be obtained by making the copies with a process of high contrast. Although this may improve the appearance when copying documents with letters of uniform blackness, it also exaggerates any differences in the blackness from one document to the next, or between the letters on a single page. In practice, the greatest working tolerance is obtained by operating the process so that the deepest black of any document is recorded as not quite black, while the whitest paper is recorded as a light grey. The copies must thus inevitably record the entire tonal range of all the documents to be copied, and this can be done without appreciable loss of legibility (*Figure* 71). This was the method used to secure a satisfactory average level of legibility in the " Airgraph " process, when many of the originals were of poor quality as a result of being written in " active-service " conditions (*Figure* 72).

Exposing Technique

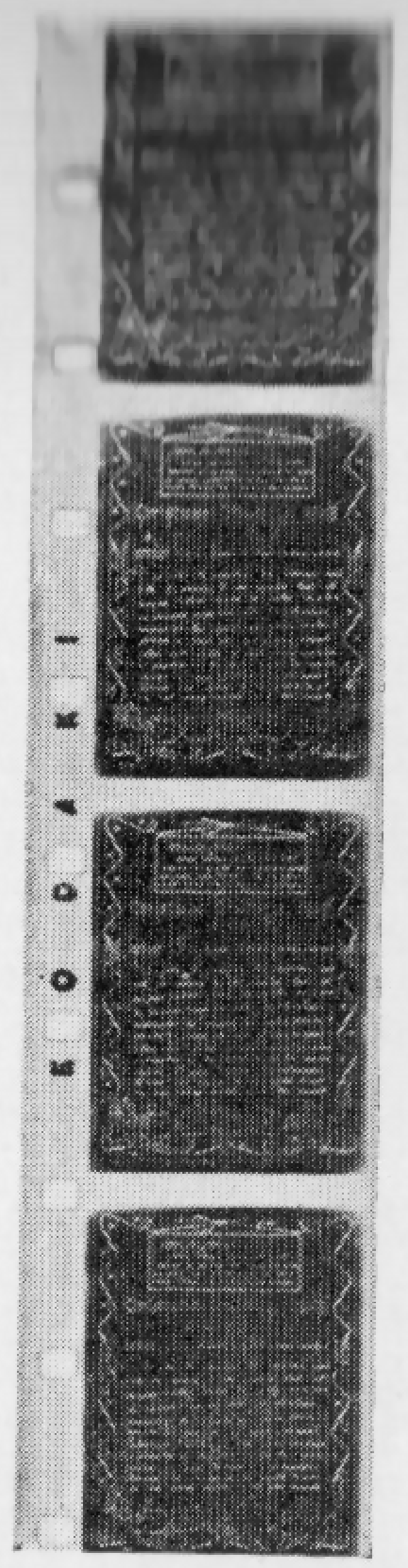
The most critical stage in the operation of document-copying processes is the exposure of the negatives, and the choice of exposure level merits careful thought. The best level is not immediately obvious, since a compromise must be sought between a heavy exposure giving high contrast, and a lesser exposure which keeps the



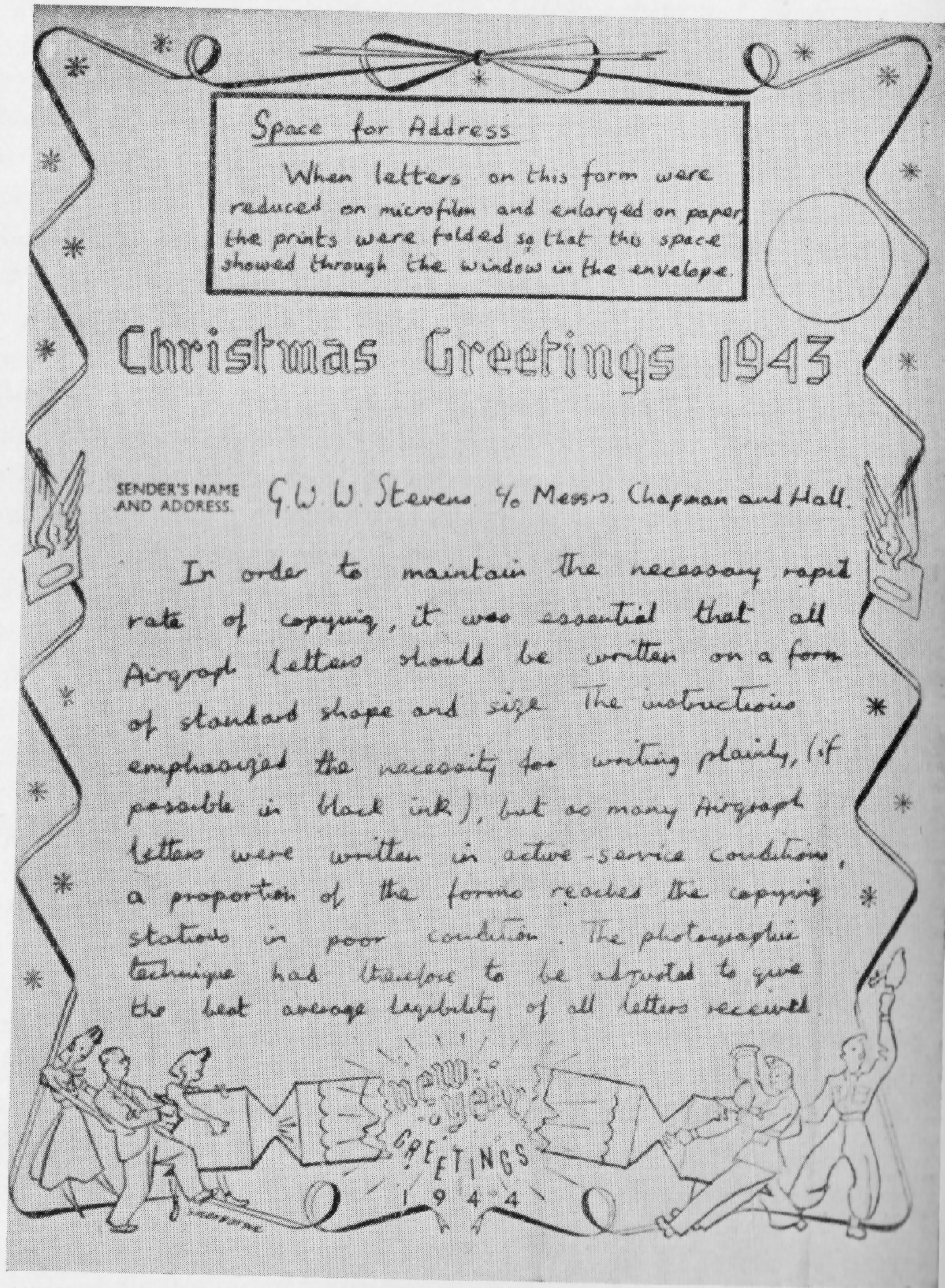
into the rinse water, carrying with it a considerable quantity of the solution. This quantity varies with the speed of the film, the design of the machine, and the efficiency of such devices as may be present to prevent "carry over." If the surface of the film carries no surplus layer of liquid, there is in the gelatin of motion picture positive approximately one quart of solution per thousand feet. High speed and absence of devices to remove the surface layer may triple this figure. This solution loss, then, represents a definite *minimum* quantity of liquid that *must* be added to the system as a whole to maintain its volume constant. This quantity frequently is insufficient and more must be bled away so that the desired amount of replenisher may be introduced without overflow-

FIG. 71. *Influence of Contrast on Legibility.*

Although the contrast of the left-hand part is lower, little legibility is lost. Images such as this, with some density in the background and letters not completely black, can be relied on to record even the faintest inscriptions, and not to clog the strongest.



(*a*) 16-mm. film bearing row of images.



Space for Address

When letters on this form were reduced on microfilm and enlarged on paper the prints were folded so that this space showed through the window in the envelope.

Christmas Greetings 1943

SENDER'S NAME AND ADDRESS. G. W. W. Stevens c/o Messrs. Chapman and Hall.

In order to maintain the necessary rapid rate of copying, it was essential that all Airgraph letters should be written on a form of standard shape and size The instructions emphasized the necessity for writing plainly, (if possible in black ink), but as many Airgraph letters were written in active-service conditions, a proportion of the forms reached the copying stations in poor condition. The photographic technique had therefore to be adjusted to give the best average legibility of all letters received

(*b*) Enlargement from single frame to size legible with the naked eye.

FIG. 72. *Negatives and Enlargement produced by the "Airgraph" Process.*

Courtesy of Mr. K. Stuart-Smith. Recordak Division, Kodak Ltd., London.

[*Facing p.* 251.

images of the lines " open ". To understand the necessity for this compromise, we must examine the influence of exposure level on the quality of document microphotographs.

It has previously been shown (*Figure* 21) that the characteristic curve of silver-halide-gelatin emulsions starts with a " toe " having a very small slope, and the slope increases with exposure until the " straight-line " portion of the curve is reached. Thus the effective contrast of a negative depends not only on the emulsion and development used, but also on the exposure ; and increases progressively with exposure until the entire density range corresponds to the steepest part of the curve. Increasing the exposure is hence an effective way for increasing the density range of an under-exposed image.

The importance of keeping the images of the lines open is easily seen by considering the enlargement of a negative from a document with lines of uneven strength. As shown in the preceding section, different lines may vary with respect to blackness or width, and in the negative strong lines will be reproduced by lower densities than those of weaker lines. During enlargement the finest reproduction of any line is given by the least exposure producing adequate density : an increase beyond this point resulting in broadening of the lines and a coarsening of the image. It therefore follows that the degree of over-exposure (and hence of broadening) suffered by the strong lines will depend on the range of density in the lines, when the printing exposure is adjusted to the minimum giving an adequate image of the weakest line. For this reason the range of line density should be kept as small as possible, and this is achieved by exposing so that the lines are all recorded on the low-contrast " toe " of the curve (*Figure* 73).

From practical experience it has been found that the best average quality is obtained by exposing " Micro-File " film to give background densities in the range 1·2–1·5 (above base), although the emulsion is able to give much higher densities. It has, in addition, been proposed that documents be sorted into classes according to the strength of their lines, and those with weak or faint lines should be given a somewhat reduced exposure.(22) In such cases maintaining the " openness " of the lines is more essential than the extra contrast which would be obtained by raising the exposure level.

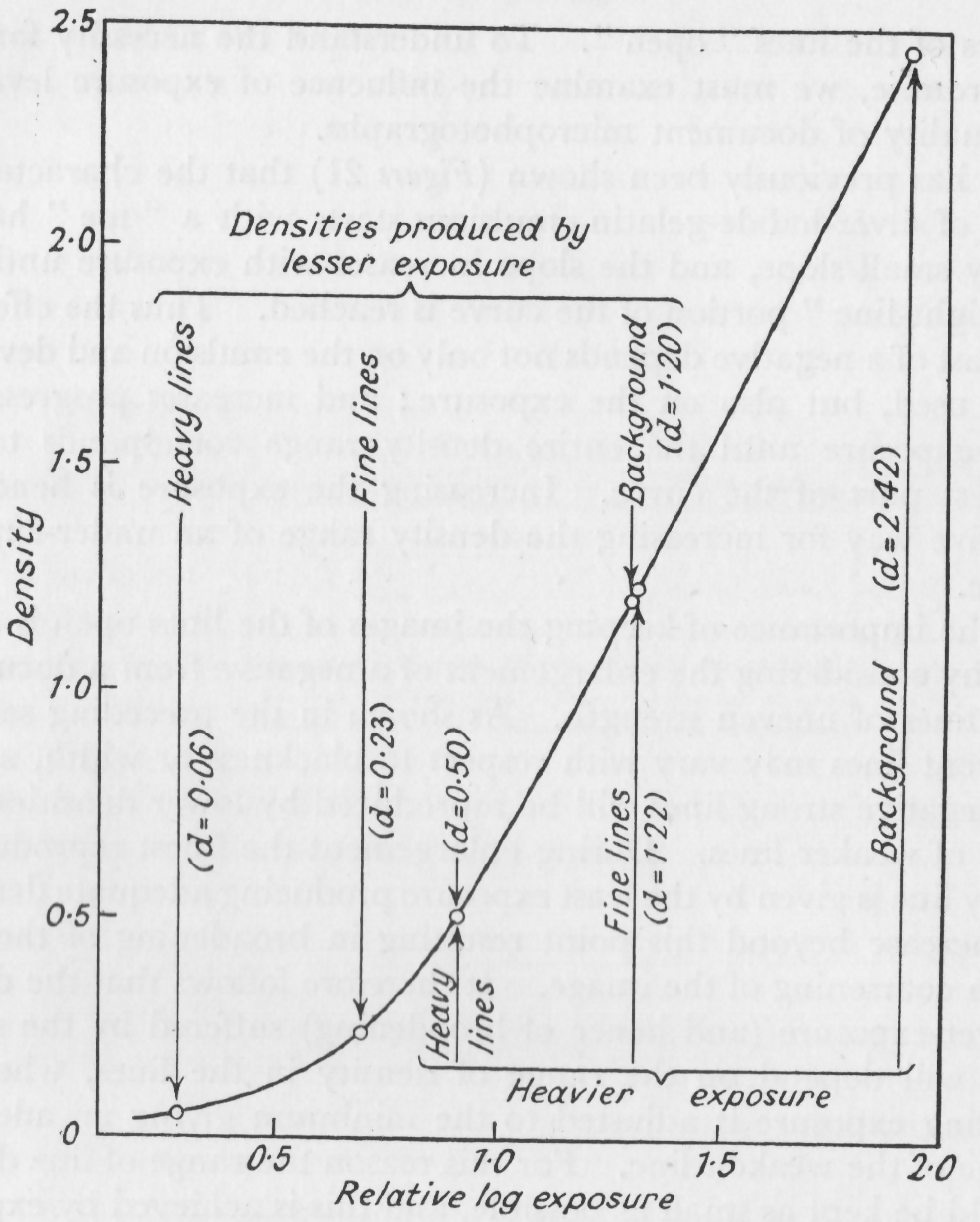


FIG. 73. *Influence of Exposure Level in Document Copying.*

Densities produced by different parts of the image are given in brackets. With the lesser exposure the difference between heavy and fine lines is 0·17, and with the heavy exposure 0·72. The heavy exposure only increases the useful fine-line-to-background difference from 0·97 to 1·20.

Negatives with higher densities and more contrasty images are normally used when they are only intended to be read by direct projection, since legibility under these conditions is disturbed much less by differences in the densities of the lines.

Precise control of exposure level to give negatives of consistent background density is obviously useless if the illumination of the document is not uniform. Uniformity depends on suitable placing

of the lamps, which is cared for by the construction of commercial-document-copying equipment. Uneven illumination may, nevertheless, result from stray reflection from an operator's white coat, and can be particularly troublesome when the original documents are held under glass.

Consistency over long series of exposures is maintained by employing a photo-electric cell to control the brightness of illumination. One admirable method is to allow the light reflected from the original to fall on the photo-cell, and then adjust the lamp voltage to bring the light reading to a definite value. This technique compensates for variation in the whiteness of the paper as well as for changes in mains voltage, and should result in negatives of consistent background density. Photo-electric light meters are built into the more elaborate commercial-document cameras. The production of satisfactorily consistent results is also helped by keeping the objective really clean. Methods of inspecting and cleaning have been described by Rudd.(22)

There are a number of subsidiary precautions which contribute much to the efficient working of commercial processes. It is, for instance, obviously desirable that the images of the documents should be " framed " so that they accurately fill the space available on the film. In one form of equipment this is achieved by projecting the image of a graticule on the page to be copied, and using this image as a guide both to the degree of reduction and the precise placing of the document on the copyboard.

The copying of very heavy or thick books, such as bound copies of newspapers or of some scientific journals, is another problem. One solution is provided by the " Recordak " book holder, which holds the two sections of the open book on platforms supported as the pans of kitchen scales. The same equipment uses a hinged glass cover for holding the pages down during exposure. This eliminates the tendency of the pages of the book to creep back after turning. " Page-creep ", or the tendency of the binding to cause the pages to move during exposure, can produce unexpected defects in quite a considerable proportion of images. The normal practice with small books is to copy two pages together at each opening of the book, but in the case of newspapers the large pages and the small size of the print make this impracticable. A " shuttle " copyboard has therefore been designed which allows the whole book to be rolled to and fro, so that alternate pages can be brought underneath the camera without undue effort.

Although spoilt exposures should seldom occur, " retakes " of any images which are known to be spoilt are best done immediately after the faulty exposure. This is clearly more economical than splicing the missing image into the film at a later stage.

Processing

The main problem in the processing of microfilms is that of handling long lengths of film. Short lengths of 35-mm. or 16-mm. film or cut-sheet microfilms can be handled by methods used for " snapshot " photographs ; but the handling of film in lengths greater than a few feet requires special equipment. The most efficient method, giving the lowest processing cost per unit length of film, is to employ a continuous-processing machine of the type used for handling many thousands of feet of cinematograph film each day. The majority of users of microfilm in fact take advantage of commercially-available continuous-processing facilities which offer sensitometric control of quality : frequently with a 24-hour service.

Some users, however, prefer to process their own films, and their output will usually not justify the cost of a continuous-processing machine. There are basically two types of equipment which can be used for smaller scale operation. One type loads the film into a metal or plastic spiral, which holds successive turns apart so that the solutions can have free access at all times. The " Stineman " and " Nikor " spiral reels are types available for 100-ft. lengths in the United States, while a spiral holding 100 ft. of 35-mm. film (" Kodak " Spiral Film Processing Outfit) is available in Great Britain.

The other type is in principle similar to the " roly-poly " machines (used for processing aero film during World War II), in which the film is wound backwards and forwards between two reels under the surface of the solution. The emulsion picks up developer during its short travel through the solution, and this film of solution is allowed to act until the motion is reversed and the film is rewound on the other reel. Although this method would be expected to give non-uniform results, practical experience has shown it to be reasonably satisfactory. Hand-cranked equipment of this type (Williamson, Morse and Fairchild-Smith) is very moderately priced but tedious in operation. Motor-driven models are made by Fairchild-Smith and the Microrecord Corporation, and incorporate mechanisms for reversing the drive with very little " jerk " when practically all the film has been wound on to either of the reels.

The processing solutions for document microphotography are of conventional type, but this work demands strict attention to details. The occurrence of avoidable errors in processing decreases the effective working tolerance for the exposures. Development should therefore be for a fixed time at a definite temperature, preferably also in fresh solution. Fixing and washing are also important, particularly when images of good keeping properties are desired. In this connection, the National Bureau of Standards of the United States of America has stated that the residual hypo content of microfilm should not exceed 0·005 milligrams per square inch.(9) It has been found that silver thiosulphate is more difficult to wash out than hypo itself, and hence that the achievement of this standard of residual hypo is facilitated by thorough fixing. This can be achieved economically by fixing first in a partially exhausted fixing bath until the opalescence is removed, and then re-fixing in a fresh bath. The silver salts and hypo will then be more rapidly eliminated by washing, which must in any case be thorough. Hypo eliminators can also be used to destroy the residual hypo in the emulsion layer, and special tests have been published for the estimation of residual hypo in processed film.

The elimination of hypo has so far proved to give apparently satisfactory stability, but even more effective precautions can be taken to preserve photographic images. These have already been discussed in the section on the preservation of records and archives. The life of document microphotographs will, in any case, depend on the conditions used for storage : a question which has been discussed in the literature.(10)

Microscopic Document Copies

The whole emphasis of the preceding sections has been laid on the mass-production methods which are essential for the copying of very large numbers of documents. These processes depend on the production of copies of such dimensions and under such conditions that the probability of any image proving unsatisfactory is very small indeed. Now it is not difficult to produce excellent document copies with much smaller dimensions than those used for commercial processes (*Figure* 3), and at intervals it has been suggested that greater degrees of reduction should be used. It has, however, yet to be demonstrated that the necessary large quantities of these smaller images can be made economically.

A number of practical disadvantages attend the use of an excessive degree of reduction. As the image size is reduced beneath a certain limit, the extra resolution can only be obtained by using emulsions with still finer grain, and having much less speed. Substantially greater exposures are therefore required. Now the brightness of the reduced image of an opaque document is determined by the amount of light thrown on to the page, and by the effective numerical aperture of the objective. With opaque originals there is no significant increase of image brightness as the degree of reduction is increased (Chapter 8). For these reasons the exposure required for copying each page directly on a concentrated-Lippmann emulsion would be inconveniently long, even if the documents are illuminated by an arc lamp. It thus becomes impracticable to achieve the full degree of reduction in one stage, and a faster emulsion must be used to produce reduced " intermediate " negatives, from which the minute images can be produced by a second reduction. This is clearly a major inconvenience, sufficient by itself to hinder seriously the general use of the smaller image sizes. A further point of some importance is that processes using 35-mm. or 16-mm. film give images which can be legibly multiplied by contact printing or by a cinematographic projection printer. Duplication by contact printing is practically precluded by the use of microscopic images (see Chapter 10).

When the advantages of microscopic document copies are sufficient to repay the extra trouble involved, the technical approach should be quite different from that used for commercial-document-copying processes. The work should be organized so that every image is effectively inspected, and so that an appreciable proportion of rejected images will cause a minimum of inconvenience. It is interesting to note that the necessity for inspection of microscopic images has been repeatedly described in the literature. Commercial workers of the period 1860–75, for instance, customarily made many images on one plate, and discarded those which were unsatisfactory.(23) Goldberg even continued to examine his images at intervals during the exposure (Chapter 6). A further example is given by an apparatus developed by the Nazis for the production of espionage " microdots ". This had a reversible optical train which allowed the microphotographic objective to enlarge the images so that they could be inspected before dispatch.(24) The general technique for making microscopic document copies is the same as that described in Chapter 9.

Reading

Document microphotography is useless unless apparatus is available for reading the copies, and this need for an optical aid constitutes one of the main objections to the use of microcopies. We have noted that part of these objections can be traced to the personal habits or preferences of the reader, but others can be attributed to the difficulty of devising the ideal reading machine. The spread of cheap and convenient machines will do much to widen the use of microphotography.

Reading aids can either take the form of visual magnifiers, or may more commonly consist of optical projectors. In the former, the eyes have to be placed so that they can see an enlarged virtual image produced by the magnifier, and the head has to be held in one definite position. The projection systems, however, throw an enlarged image of the microcopy on an opaque or translucent screen so that the reader is free to move his head and can sit in a natural and comfortable position.

Visual Magnifiers

The main merit of visual magnifiers is their cheapness and simplicity. They consist essentially of a frame for holding the document copy at a fixed distance from the magnifying lens to which the eye is applied. Quite effective reading aids disguised as matchboxes were made from cardboard with a plastic lens, and were used by the " underground " forces in Europe during the Nazi occupation.

Visual magnifiers are obviously limited in their scope. In their simple form only one eye can be used for reading, and the useful magnification is not beyond 10 diameters. In short, they are uncomfortable to use, and are better suited for " scanning " the documents to discover their subject-matter than for actually reading them.

Some workers have used more elaborate equipment such as binocular magnifiers of the type used for biological dissections. Such instruments are not cheap, and their use is only likely to find favour when they are already available. At the other extreme, the compound microscope is needed for the reading of truly microscopic document copies. Satisfactory illumination for reading can then be obtained by the methods ordinarily used for visual microscopy.

Projection Apparatus

Transparent microphotographic document copies can be read with the aid of slide projectors of the type used for film strips, or for the projection of 35-mm. colour slides. Although the optical performance of such instruments will often prove adequate, they are not equipped with the devices for moving or locating the film, which are really needed for convenient reading. Many different types of projector have been specifically designed for this purpose, and these are of two types. One has a compact projection unit which throws the image on a sheet of paper, whereas the other projects the image into a dark box with a translucent screen at one end. The screen is placed between the reader and the projection unit, and must scatter just enough light to prevent the user from seeing a " hot-spot " of light in the centre of the screen, without seriously reducing the intensity transmitted by the screen. The translucent screen allows a much higher proportion of the light passing through the document copy to enter the eye, since the light from the projected image is less widely scattered than in the case of projection on an opaque screen. Less powerful illuminants need therefore be used, and translucent screens are thus of assistance in preventing damage to the microphotographic images by overheating during reading. Against this must be set the fact that the appearance of the document projected on a translucent screen is less natural than on an opaque screen, and the images lend themselves less easily to manual copying. For reasons such as these, some librarians strongly favour opaque screens, and this preference has been supported in a review issued by the Organization for European Economic Co-operation.(25) Readers of this type have also been developed for projecting images on hospital walls or

ceilings, and thus permit patients who cannot hold a book to read in comfort.(26)

Let us now consider some of the other properties of reading aids which are likely to be noticed by their users. The enlarged image should be almost as sharp and contrasty as the image in the film, and without obvious colour fringes. It is also advantageous for the whole field to be in focus at the same time, so that the eyes do not have to contend with a change in sharpness when reading along a line or down the page. In this connection it can be stated that sacrifice of optical quality for the sake of cheapness is a false economy, and is definitely not worth the eye-strain which is likely to result. The projector should give an image of comfortable brightness, preferably sufficient to allow the copies to be read without darkening the room. This means that the document copies must be subjected to an intense illumination without overheating, since their useful life may otherwise be seriously shortened.

The brightness of the projected images is also connected with other features of the document-copying process being used. Thus we have already noted that translucent screens make it easier to achieve a satisfactory standard, as does the avoidance of great degrees of reduction which necessitate large magnifications. The use of great degrees of reduction, of opaque viewing screens, and of opaque microcopies such as " Microcards " all aggravate the problem of achieving satisfactory illumination. In the case of transparent film, a " negative " copy, in which the letters appear clear against a black background, will absorb most of the incident light, and thus get much hotter than a " positive " copy of the same dimensions but with black letters on a clear background.

Other factors which influence the convenience of microfilm readers are :

The arrangements for focusing and for advancing the film from one frame to the next.

A size of field permitting a whole line or column of print to be read without moving the film.

A swivel-head allowing images lying in any direction on the film to be brought upright.

Means for loading the film which are simple to operate, but minimize the risk of damaging the images.

In all but the most recent readers for roll microfilm, the film is held flat for viewing by being pressed between two flat glass surfaces, which are separated automatically when the film-winding handle is turned. This means that the images go out of focus during winding, so that the movement has to be stopped and the pressure re-applied before the page numbers can be read. This defect has recently been overcome by replacing the fixed register glasses with a pair of rotating glass discs (*Figure* 74), permanently separated by a space slightly deeper than the thickness of the film. When the film is wound on, rotation of the discs allows it to travel through this space without damage, while the up or down movement is so small that the image is always in focus. This feature is incorporated in the recently introduced American " Recordak " film reader PE-40, and the " Kodagraph " Model MPE. A further advantage of this mechanism is that it prevents the sticking which sometimes occurs when the film is held between normal register glasses and is left in the gate for a long time.

Before concluding this section, we should note that the provision of convenient readers is of the utmost importance for the spread of microphotographic processes, particularly for scholarly applications. Unnecessary inconvenience will tend to distract the user, thus hindering concentration on the text being read, and causing the hardening of prejudices against microphotographic document copying.

Enlargement

Microphotographic document copies on film can be used for making enlargements legible with the naked eye, so that the user can study the document in any convenient place. Negatives to be used in this way should be particularly sharp, since slight unsharpness tends to be more objectionable when viewing a print rather than a projected image. Experience shows that negatives intended for subsequent enlargement should have a lower background density than those made for direct reading with a projector (see section on exposing technique).

Enlargers designed for use with 35-mm. miniature-camera negatives can be used for making moderate numbers of enlargements from microfilm negatives, but they are not ideally suited for the purpose. They are not usually designed for use at magnifica-

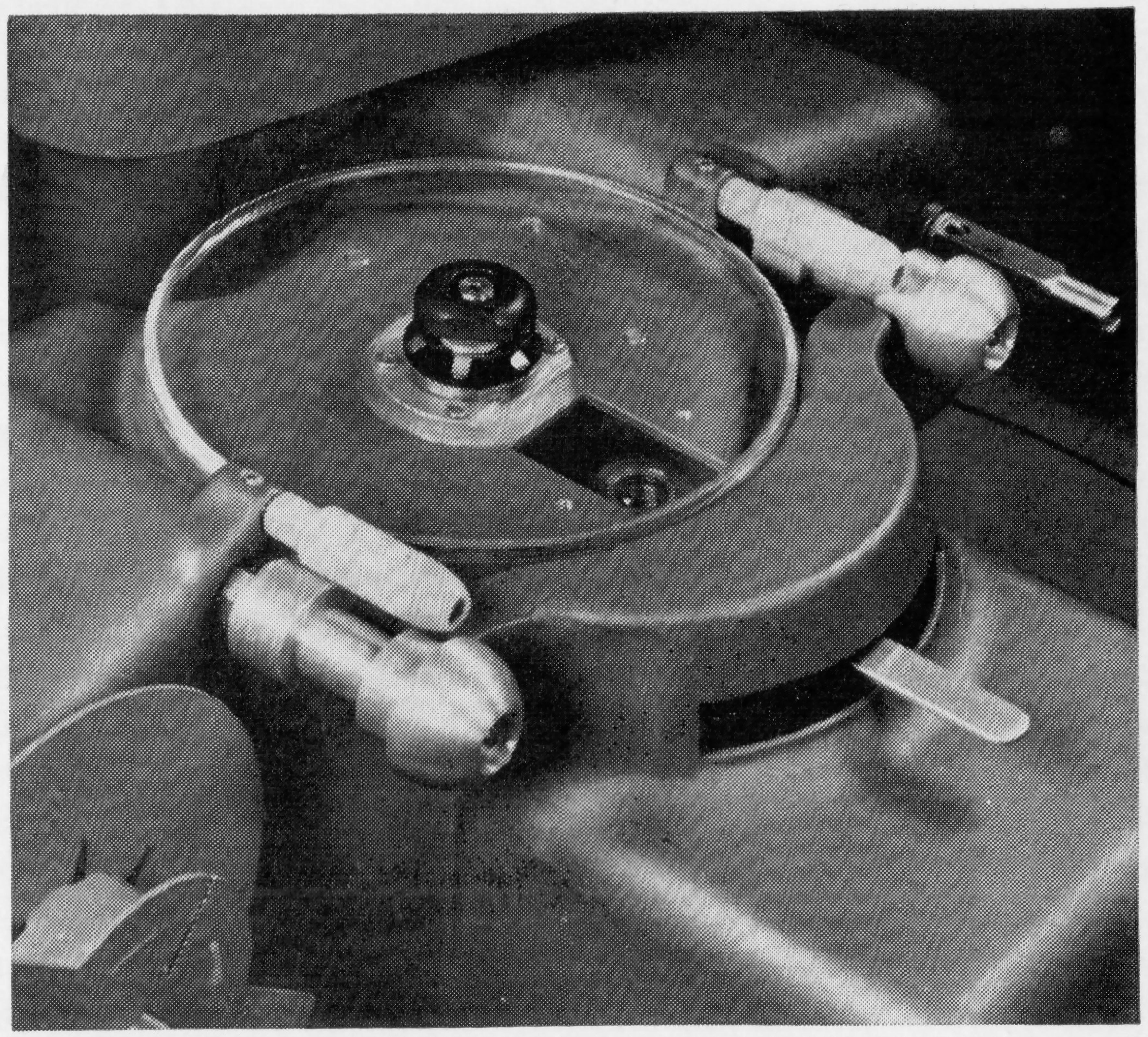


FIG. 74. *Rotating Register Glasses maintaining Focus during Movement of Film.*

Pair of glass discs in " Recordak " Film Reader, Model PE.40. The film can pass freely between the discs, but the clearance is so small that the image is kept in focus continuously.

Courtesy of Mr. C. H. Green. Eastman Kodak Co., Rochester, U.S.A.

[*Facing p. 260.*

tions greater than 10 or 15 diameters, whereas document work can require 20 diameters or more. It is also possible that the corners of the image projected by lenses designed for pictorial photography may not readily show the crisp definition required for document copies. All but specially selected objectives may, therefore, have to be drastically stopped down.

Various manufacturers of equipment for document microphotography have now introduced enlargers specially designed for this work. Most of these enlarge one frame at a time, but continuous enlargers were made for use with the " Airgraph " and " V-mail " services. The film was moved continuously past the objective, and the band of paper was moved in the opposite direction at a rate proportional to the magnification, so that the projected image was stationary on the paper.(14) The paper was also processed on continuous machines, and these two principles permitted an enormous volume of work to be handled.

There is also a potential demand for an enlarger which scholars can use for themselves. With the existing types of reader the user must go to the machine in order to read microfilms, and this is inconvenient for scientific workers whose reading occupies a smaller percentage of their total working time than is the case in other scholarly pursuits. This makes it probable that they will not read microfilms if they can avoid doing so. A possible solution might be the introduction of an enlarger-scanner, allowing the scanning and selecting of wanted pages, and the production of the enlargements all on one machine.(25)

Existing Systems

Commercially-operated processes for microphotographic document copying may be classified according to the final disposition of the images. Some processes produce a *linear array* by making successive exposures along a length of film, whereas others produce *two-dimensional arrays* in which rows and columns of images fill the area of a rectangular film or card.

Linear-array Systems

" Miniature " still cameras, or a ciné camera giving single-frame exposures, can be used to produce strips of film bearing a row of document copies, but such instruments are not particularly convenient for this work. Their use is likely to prove uneconomic if more than a very small volume of work has to be done. Much ingenuity has gone into the designing of special equipment for doing this work with the maximum speed and convenience. Apart from achieving the necessary image quality, the designers have concentrated their attention on three main features of great commercial importance :

(i) maximum efficiency in the use of the available area of film,
(ii) great dependability,
(iii) simplicity of operation and speed of output.

Their efforts have led to the development of two quite different types of equipment, one form reproducing moving documents on moving film, and the other exposing successive stationary areas of film to the images of stationary documents. Apparatus with the moving film is exemplified by the " Commercial Recordak ", which was the pioneer instrument in this field. With this machine the document is passed into a slot, from which it is carried round a continuously-rotating drum. As soon as the document reaches a certain point in the mechanism, it moves a lightly-loaded trip bar. This actuates a sensitive micro switch, which turns on the lights and operates a clutch driving the film in the opposite direction to the document, and at a rate proportional to the degree of reduction, so that the aerial image of the document remains stationary relative to the film. The normal rates of reduction are 17 or 23 diameters and the film therefore moves at one-seventeenth (or one-twenty-third) the speed of the document. The length of the exposure is determined by the rate of rotation and the width of the slit behind which the film moves. As soon as the end of the document passes beneath it, the trip bar returns to its original position and the lights are turned off and the film stopped ; but the document travels through the machine and arrives at the exit chute. By this arrangement, film is only exposed and moved while a document is actually in the position for copying. This prevents wastage of film, and ensures that the individual images are conveniently spaced, whatever the length of each document happens to be. Such machines are very simple to operate, and will accept documents almost as fast as they can be fed in. Some operators feed alternately with each hand, and can copy cheques at the rate of 5,000 an hour.

Many refinements have been built into available machines of this type, and the following special features of some machines may be noted :

(i) The machine may only accept one document at a time, and stop automatically to prevent missed images if two documents are inserted together.
(ii) Crumpled documents are straightened automatically.
(iii) Selector switches permit either one, or both sides of the document to be copied.
(iv) Readily-interchangeable units allow the degree of reduction to be changed with a minimum of delay.
(v) An accessory will endorse each cheque, and record the fact that it has been copied.
(vi) Automatic feeding from a stack of documents raises the output of the machine, and double cameras can be used to make two separate but identical records when duplicates are needed.

Although such refinements must necessarily increase the initial cost of the equipment, in suitable circumstances the increased output will easily justify the expenditure.

The automatic linking of the motion of the film and the documents, together with the use of a fixed focus and fixed illumination and aperture, makes the moving-document systems unrivalled for ease and speed of operation. The copying equipment, however, is necessarily limited in scope and flexibility, and is best suited for straightforward tasks where a high rate of copying is all-important. These processes are particularly well adapted for the copying of cheques, invoices, letters and other single-sheet documents which do not contain exceptionally fine detail.

The systems using a stationary film and document mainly employ cameras mounted on a vertical pillar and with the original left flat on a table. In essentials such cameras are not unlike a ciné camera, which has been modified to allow individual frames to be exposed to successive documents or pages of a book with economy of effort and film. Varying degrees of reduction are obtained by raising or lowering the camera on the pillar. The Recordak " Micro-File " machines were also pioneers in this field, and equipment for this type of work is now made by other firms including " Microstat ", " Graflex ", " Remington Rand " and " Burroughs ". Apparatus providing a continuous series of degrees of reduction obviously confers much greater flexibility when working, but also needs more attention in operation than the moving-document units. The successful operation of variable-reduction systems is assisted by devices reducing the need for personal judgement ; these include :

(*a*) determination of the degree of reduction by using a plumb-tape from the lens to the copyboard, and focusing by scale according to the reading on the tape,

(*b*) fully-automatic focusing coupled mechanically to the vertical adjustment of the camera,

(*c*) indication of the field copied by projecting on the copyboard an image of a movable mask, which is linked to the film-transport so that a thin line separates successive images,

(*d*) exposure controlled by photo-cells,

but only very expensive machines incorporate most of these refinements.

In many instruments the exposing routine is almost completely mechanized. Thus in one camera the exposures are made by pressing a foot switch once the instrument has been adjusted for document size. An electric motor then actuates a suction device holding the film flat in the focal plane, operates the shutter, records the exposure and advances the film, all within a time of one second. As a result, both the operator's hands are free to turn over the pages.

The economical working and reliability of all types of linear-array copying apparatus is greatly aided by various safety devices and alarms which indicate if anything is not operating satisfactorily.

Not all apparatus of this type is complex and expensive, and equipment such as the " Recordak Junior Microfilmer " has been designed for offices handling a smaller volume of work. This consists of an open-fronted cabinet containing the lamps, in which the bottom serves as a copyboard and projection screen. The camera and projection units are both located on the top of the box. To operate this instrument, the documents are laid on the copyboard between guides, and a movable guide-bar is moved across

the document to advance the film by just the amount needed. To make the exposure, two separate buttons have to be pressed simultaneously, so that the operator is forced to use both hands, and cannot, therefore, obscure the document. Only a moment is needed to convert the instrument to the reading position, and documents can be read while the camera is still loaded with unexposed film. Dual-purpose machines, which can be used both for producing and projecting microfilms have also been developed by the Microstat Corporation.

Systems giving Two-dimensional Arrays

Historically, the commercial development of document microphotography has been stimulated mainly by administrative users, in particular by bankers.(8) Modification of motion-picture equipment provided systems giving linear arrays of images on rolls of film, and these have adequately served the demands of many users. This line of development has, however, been regarded as a retrograde step by some librarians and readers handling scholarly material, who have likened it to a return to the primitive scroll books which preceded the more convenient bound books. The arrangement of the images to fill the area of a flat sheet or card is considered to be superior, and to provide a level of convenience in the finding of any page comparable with that of the bound book. In addition, further copies from sheet negatives can be made simply in a contact-printing frame, whereas elaborate printers are needed for making additional copies of roll microfilm. Opinions of this kind have initiated a powerful trend towards the adoption of document-copying processes giving microphotographs in the form of flat sheets or cards filled with rows and columns of images.

An early suggestion for the use of two-dimensional arrays was made by Goldschmidt and Otlet,(27) who proposed that fifty or more pages should be copied on a 5 × 3 in. (12·5 × 7·5 cm.) card. The idea was taken up by van Iterson and others,(28) while Fremont Rider made a number of proposals for using such cards to relieve the congestion in technical libraries, and at the same time increase the accessibility of the information stored.(29) His main proposal was that the full text of articles and books should be reproduced on one side of 5 × 3 in. filing cards, while bibliographical details and classification would be recorded on the back in print legible to the naked eye. The effect of this suggestion is that the scholar has only to find the index card of any article, and the complete information it contains is immediately at his disposal.

Two-dimensional arrays of document copies can be made by using one exposure with a single lens to copy many pages (or photographic copies of the pages) of the original document. By this means the assembly of the pages into rows and columns is achieved before the final reduction. Two difficulties are that it becomes impracticable to change the exposure from page to page, as may be necessary when dealing with some types of original; and an objective must be found giving adequate sharpness over a much wider field.

An early practical execution of Fremont Rider's scheme was realized as a result of co-operation between the Microcard Corporation and the Eastman Kodak Company, and a detailed account of the methods used for making microcards for internal use by the Eastman Kodak Company has been given by Kuipers.(30) The articles are first copied on unperforated 16-mm. film by using a standard type of stationary-film linear-array camera. Two pages are copied with each exposure, so that the images lie side by side along the length of the film. Six successive exposures thus provide images of twelve pages in a total length of 4$\frac{3}{4}$ in. (12 cm.) and the film is then advanced for three frames without exposure. After processing, the film is slit on a manually-operated machine so that 1 mm. (0·04 in.) is removed from each side of the 16-mm. film. It is then cut into lengths, divided at the blank frames, and registration holes are punched on the blank space at the ends of each length. Five such lengths are then mounted on pins on a negative-strip carrier, so that they are held accurately side by side in front of a mask to prevent the formation of black edges during printing. After printing by an automatic printer on a continuous roll of special paper and processing continuously, bibliographical details are printed on the back of the cards with a " Multilith " machine. The negative strips are finally filed in a very small space in case further copies are required at a later date. Articles of doubtful interest are inserted directly in the file, and are only printed when the demand arises.

A noteworthy feature of this scheme is that the cost per copy of making the microcards becomes quite small when a number of

prints are made. The user can thus obtain the full text of a scientific article for the cost of little more than a picture post-card.

The Microcard Corporation has used similar methods for preparing copies of inaccessible or expensive literature for distribution to scholars. In effect they use the process as a method of re-publication. The first titles include much literature of historical and literary interest such as:

Bell's *British Theatre* (collections of plays),
Chaucer Society publications,
Early English Text Society publications,
The New England Historical and Geological Register,
The Chronicles and Memorials of Great Britain and Ireland in the Middle Ages.

The scientific works include a few journals in the English language, but these are mainly journals with a rather limited circulation. The German-language journals, however, include such standard sources as:

Physikalische Zeitschrift,
Annalen der Physik,
Kolloid Zeitschrift,
Beilstein's *Handbuch der Organischen Chemie*, 1865–1945.

The latter work is the most comprehensive existing catalogue and index of organic compounds and their properties and methods of preparation. Modern material in the English language is represented by microcards of U.S. Patents (*Figure* 2), and by theses submitted for degrees, containing such titles as *Microwave Technique in Chemical Kinetics.*

Although the list of works published on microcards is impressive, there are clear indications of the difficulties the publishers must be experiencing from the restrictions imposed by copyright. Thus a very large proportion of the material offered is more than fifty years old, so that the original copyright has lapsed. The inordinately high proportion of German titles in the modern scientific journals is also interesting and might be attributed to the limited availability of these works and to a temporary easing of the copyright restrictions resulting from the Second World War.

Systems producing Two-dimensional Arrays Directly

Kuipers' system has already proved itself as a workable method for producing microcards, but it has obvious disadvantages. The separated lengths of negative must be assembled afresh each time a print has to be made, an operation introducing the possibility of error and wasting time. This can be avoided by making the original exposures so that the images fill the areas of a rectangular sheet of film, and two methods for achieving this have been used. In one system (the " Polydoc " invented by Cordonnier), successive exposures produce rows of images side by side across the width of 6-in. (15-cm.) wide film, and the film is advanced by the height of one row before the next row is started.(28) The images can thus be formed in a two-dimensional array filling any desired length of film, and the whole roll may be printed as a single unit, and the individual sheets obtained by cutting the prints into the desired length.

Another possibility is to make the exposures directly on sheet film or on plates, and provide a movable cassette, so that the images are spaced in rows and columns as they are exposed. This principle has, of course, already been used in photomechanical work to make " step-and-repeat " exposures (as in assembling blocks for postage stamps), and for multiple-exposure portraiture by the " Photomaton ". Van der Wolk and Tonnen (28) have reviewed a number of systems applying this principle to document copying, including those using the Kabitz and Goebel cameras. The former employs a cassette which is moved by hand, in such a way that its position for each exposure is controlled by a peg sliding in a grooved channel. The Kabitz camera provides a simple and inexpensive solution to the making of sheet microfilm at a fixed reduction and with 16 exposures (usually of two pages) on one film, but the speed of operation is relatively low. It should, therefore, satisfy the needs of a small research institute, or even the individual worker.

The positioning of the cassette on the Goebel camera is automatic, and is effected by interchangeable bars containing notches corresponding to the numbers of rows and columns to be produced on a sheet. The degree of reduction is also adjusted to suit the size of the documents to be copied and the number of images on one sheet—as controlled by the notched bars. This system is clearly very flexible, since it permits the ratio of the height to width of film used for each exposure to be varied to suit the dimensions of particular documents. The Goebel camera also contains a subsidiary objective for printing directly legible bibliographical details across the top of the film, and its higher degree of mechanization allows a greater volume of work to be produced.

It is not obvious which of the systems for making two-dimensional arrays of images will ultimately prove most successful. Kuipers' system is not claimed to be anything but an interim solution to the problem, but it has the advantage that the same cameras can be used for making conventional roll microfilm or microcards. Cameras using sheet film have the advantage that a microcard of any particular subject can be produced with a minimum of delay, as the sensitive material is handled in single units. On the other hand, the labour cost of processing each sheet is highest when they are handled singly ; but the output of a single camera is not sufficient to justify installation of a continuous-processing machine. Sheet-film or plate cameras may thus provide the most convenient systems for handling only a limited volume of work. Beyond this point the need for automatic processing is felt, and it is in this field that Cordonnier's arrangement should excel. There seems no reason why this system should not ultimately give sheet microfilm at a cost per page not much in excess of (or even less than) roll microfilm. Such considerations suggest that each system may find its own particular applications.

Another completely different type of process providing cards bearing a large number of microphotographic document copies is operated in the United States by the " Readex Microprint " Corporation. One hundred images are recorded on a 9 × 6 in. (23 × 15 cm.) card, and the actual cards are printed on a printing press, and not photographically. While no details have been released about the methods used, it seems certain that microphotographic methods must be employed to make the reduced negatives, from which the printing plates are prepared. Examination by printing experts has led to the suggestion that an offset-photolitho process is used for making the prints. This is obviously an economical process when very large numbers of copies of each card are required. It is, in fact, a publication process rather than a reproduction process.

Future Development of Document Microphotography

Document microphotography is in an active state of development and expansion, and some authorities consider that it is still only in its infancy. One can anticipate three directions in which future developments are likely to go. Firstly, the scale of operations will probably increase, and the number of documents copied will rise from year to year. The magnitude of this movement is, of course, of great interest to the producers of the necessary materials and apparatus. Secondly, much work and ingenuity is being expended on the improvement of materials and processes, and this should result in the removal of many of the present objections to the use of microcopies. The third direction is in the application of document copies, and their greater use for solving the problems of handling information. It is clear that developments in all these three directions will interact on each other.

The performance given by existing processes represents a notable technical achievement, but there is still plenty of scope for improvement. The use of high degrees of reduction would, for instance, be facilitated by the production of emulsions with improved resolution for a given level of speed, or by objectives giving the necessary field coverage at greater apertures, or by improved illuminants permitting slower emulsions to be given an adequate exposure without increasing the exposure times beyond present practice. It is doubtful whether such developments will ever permit the rapid production of microscopic documents having a page height of less than 0·1 in. (2·5 mm.) without the use of an intermediate negative. The scope of usefulness of document microphotography might also be extended by the use of colour materials, particularly for the microfilming of mediaeval texts or of medical and biological works.

Considerable developments can also be expected in the design of reading equipment. It is particularly to be hoped that a portable instrument will eventually be produced at a price low enough to permit individual scholars to own or at least to hire one. It seems likely that instruments being developed in France and Germany, and having the weight and price of a portable typewriter, may fill this rôle.

Until now, the greatest use of microphotography has been for the storage of information. This storage has brought the information closer to the user in a physical sense, but there is a danger that it may lessen availability by making any one piece of information more difficult to find. This problem is being tackled in several different ways. Thus, in France, roll microfilm is being cut up into short lengths, often containing only ten frames, and is being stored and filed in envelopes. The microcard or sheet microfilm in which bibliographical information is recorded at a legible size also help to make information more available. Other methods are discussed in a stimulating book by Ridenour, Shaw and Hill.(31) One method which has so far not been widely practised is to use microphotography to provide a personal library permitting all the literature for any field of study to be stored in one filing cabinet, or even in one suit-case. The realization of this aim awaits the provision of a suitable reader at a sufficiently low cost and the working-out of the handling techniques for operating such a library. In this connection, Hill describes experiments being carried out at the Massachusetts Institute of Technology. Forrester and Tate are jointly attempting to make a useful personal library by microfilm or microcard. Once such a library has been assembled they propose to develop the philosophy of its use, which is at present lacking. Hill states :

> While microfilm as a technique for reproduction is very well established, microfilm for condensing a personal library is not yet in a useful state. The reason is that we do not yet know how to use microfilm for this problem and will not learn until we have tried.

Another method is to use mechanical aids for the sorting of microfilms. Shaw points out that microfilm could not previously be used for the storage of other than " dead " material, owing to the careful pre-arrangement needed to permit finding the information. Files which are being continually supplemented cannot conveniently be recorded on roll microfilm. This medium lends itself most easily to random storage, in which unsorted papers or pages are copied. The Rapid Selector (page 240) seems to make it feasible to film letters or other data at random as received, coding each entry at least as thoroughly as for normal filing, so that microfilm replaces both the files and the indexes to files, and in such a form that the entries can be searched at rates of more than 70,000 a minute.

Shaw describes three main advantages of the Rapid Selector :

(1) The reduction of storage space while permitting rapid finding and reproduction of information.

(2) The cumulative indexing of materials from various sources. Thus a thorough searching of chemical literature may require the handling of dozens or hundreds of volumes of indexes. Once this material is coded into film, the time required for electronic searching should be a small fraction of the time required for manual searching.

(3) The improvement in the quality of organization of knowledge for administrative routines, and for scientific communications.

The need for such developments for administrative purposes is illustrated in Huxley's book on the Tennessee Valley Authority.(32) A single organization in this case had to co-ordinate the planning of flood control, navigation, hydroelectric schemes, fishing and recreation, agriculture and prevention of soil erosion, and finally the re-education of a whole community to cope with a revolution in its material circumstances.

In the field of scientific communications, Shaw quotes the index to Chemical Abstracts. This is not as detailed as is required, but an index showing every idea abstracted would be several times the size of the present abstracts. Not only would the price be prohibitive but the result would be of doubtful use, since normal searching methods would be inadequate to find the items required. The Rapid Selector would clearly be of assistance here. Moreover, it can also be used for the compiling of subject indexes from material filed at random. Shaw considers that the potentialities of the Rapid Selector are so much ahead of present methods that operational research may be needed to find how best to apply it.

Now the properties required in any system for handling information are storage capacity and accessibility of any particular piece of information. Roll microfilm has high storage capacity, but the accessibility of the information is low unless all the items to be copied can be classified and sorted before copying. On the other hand, the punched-card systems used in many large organizations are characterized by high accessibility and a low storage capacity for textual information. At the end of 1954, Tyler, Myers and Kuipers of the Eastman Kodak Company made the first public announcement of the " Minicard " project for combining the high storage capacity of microfilm with the accessibility of punched cards.(33)

The " Minicard " system uses 16-mm. film which is exposed in a special camera working at 60 diameters reduction, so that a 14-in. (35·6-cm.) high document is reduced to about a quarter of an inch (6 mm.). Two such images can hence be placed end-to-end within the width of 16-mm. film, and the individual card of size 16 × 32 mm. (approximately $\frac{5}{8} \times 1\frac{1}{4}$ in.) can bear up to 12 such images. The camera also incorporates an additional unit for exposing part of the film to form a coded system of clear or opaque dots. As with the Rapid Selector, the disposition of these dots provides all necessary information for finding each card, and the information is supplied by a paper tape which has previously been punched in a machine using a typewriter keyboard. Automatic devices can also be provided for converting code from punched cards or magnetic tape.

The film is exposed, processed and dried in continuous lengths, and is then divided by an automatic chopper into individual " Minicards " bearing both document copies and coded information. The Minicards or " chips " have a rectangular hole at one end, which serves both for registration and for assembly on a rectangular rod to form a " stick " of 2,000 cards.

The coded information is arranged in columns of 42 spaces, and as 6 spaces can denote any letter or numeral, each column corresponds to 7 characters. When 12 pages of a document have been recorded, the card may accommodate 9 such columns. The number of coded columns may be increased if fewer pages are copied, up to a maximum of 70 when text is omitted. The cards are sorted automatically by feeding them one at a time past a photoelectric reading station, which directs them according to the indication of any one digit into ten receiving magazines. A sorting rate of 1,800 per minute is anticipated.

The potentialities of this system are obviously great, since the complete texts of reports and scientific papers can be compressed into a very small space and can be inserted into or extracted from an existing file at high speed. Other features of the system are that the photographic process works at an unusually low contrast which is suitable for recording both continuous-tone and line images, and that satisfactory legibility is retained after contact printing through five or six stages. This enables any number of duplicates to be made, and extra coded information can be added at each duplication stage, so that extensive cross-indexing becomes practicable.

To summarize :

The " Minicard " project combines the following innovations :

(1) The use of very short lengths of 16-mm. film, with handling techniques enabling them to be rapidly sorted with little risk of loss or damage,

(2) The combination of complete texts with a binary code suitable for handling by digital computers, all compressed into a remarkably small space,

(3) The establishment of a routine process of document microphotography using a reduction ratio as great as 60 to 1,

(4) The use of low photographic contrast for recording continuous-tone images without sacrificing legibility of the text.

It is obvious that a system such as this has involved a great deal of development work in connection with photographic emulsions and lenses, as well as a whole range of special photographic machinery. At the end of June, 1955, it was emphasized " that the system is still in the development stage, and not yet ready for commercial use ".(34) It is not, therefore, surprising that very few technical details of the means used to achieve these remarkable results have yet been published.

Perhaps the most daring proposals have been made by Vannevar Bush,(35) who originated the Rapid Selector project. He contemplated the whole field of intellectual endeavour, and observed that there are, essentially, two levels of mental effort. There are many operations such as the collecting and sorting of information, or the classification of organisms, or materials or happenings, which can mostly be done by following fixed sets of rules. In contrast to this, there is the creative thinking which carries any subject beyond its existing boundaries. Operations of the first type are commonly needed as a preliminary to creative thinking but in themselves only make a limited use of the human brain. On this reasoning Vannevar Bush considers that such operations should be delegated whenever possible to machines. The Rapid Selector should clearly

be of use in this connection. He also points out that the brain works primarily by the association of ideas, and many valuable developments arise from the transfer of the commonplace knowledge in one field of study to another field in which their application had not previously been visualized. He proposed, therefore, that the work of creative thinkers should be assisted by a " Memex ". This might take the form of a personal microfilm library into which memoranda and notes of thoughts and conversations, as well as copies of published literature, could be inserted with a minimum of trouble and delay. Together with its storage capacity, the " Memex " should also have a sorting mechanism for extracting information on any one topic, or for tracing associated ideas through many dozens of steps. The " Memex " would, in fact, serve as a mechanical memory and a " logic " machine which could take over much of the mental load carried by the creative worker, and thus leave the greatest possible mental and nervous energy available for original thought. While there is a temptation to dismiss this suggestion as utterly fantastic, it must be admitted that Rapid Selector or " Minicard " equipment linked to suitably coded personal cumulative files would execute some of the functions of a " Memex ".

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CHAPTER 13

Microphotography as a Research Tool

Microphotography is a potentially useful tool for scientific research. In previous chapters we have seen that it can assist in bringing the literature of the subject to the research worker, and in providing the graticules needed for his instruments. The materials or techniques of microphotography can also take a more active part in scientific investigations. These applications can be classified into three main groups :

1. Testing the resolution given by lenses, photographic emulsions, special processing methods and special scientific applications of photography.
2. Investigating the " fine structure " of certain optical and physical phenomena.
3. Providing high-resolution records of X-rays or nuclear particles suitable for subsequent viewing with the microscope.

Application of Microphotography to Resolution Testing

Production of Test-chart Images

The basic principle of resolution testing is essentially simple. It consists in studying the deterioration in visibility of a test pattern resulting from its reproduction by the lens or photographic emulsion under test. For this purpose one needs to be certain that the deterioration is caused only by the properties of the component under test, and not by extraneous factors such as vibration or incorrect focus. Microphotography can be used in this work in a number of ways.

The charts used for resolution testing generally consist of groups of lines of different widths, and the results of a test are assessed by finding the smallest group in which the separate lines can still be distinguished. The decrease in size from one group of lines to the next may be as small as 10 per cent., and it is important that all

groups should be reproduced with the spaces between the lines substantially equal to their widths. Considerable accuracy is therefore required in making such images, and extreme-resolution emulsions may be usefully employed even if the images are not particularly small.(1) These materials are especially useful for making further copies of test charts by contact printing with a minimum alteration in the relative line widths.

Some resolution tests require very small images, so that the test chart itself may need to be truly microphotographic. Consider, for instance, the testing of a " process " apochromat objective which is designed to give a resolution of 350 lines/mm. at a reduction of 5 diameters. The size of the test chart is limited by the fact that the objective must not be tested at a reduction substantially greater than 5 diameters, otherwise the aberrations would be increased. The finest groups of the test-chart image must therefore correspond to more than 70 lines/mm. or a line width less than 8 μ (0·0003 in.). The production of a really sharp negative with lines of this width demands the use of microphotographic emulsions and techniques. Even smaller images, with line separations corresponding to hundreds of lines per millimetre, are needed for the resolution testing of photographic emulsions by contact printing, or for testing enlarging and projection lenses.

The production of really small test-chart images is complicated by the wide range of line widths that the images are required to have. We have already seen that the exposure needed to produce wide lines is less than that required for fine lines (Chapter 9). This means that an exposure giving satisfactory reproduction of the largest groups in a test chart will probably produce only a faint image of the finest groups, while that needed for the finest groups may cause serious image spread in the largest groups. One solution to the problem is to make the images from a large transparency, using a high degree of reduction. It is then possible to compensate for the different exposures required by placing neutral densities behind the larger images in the test chart. A less laborious method which can give acceptable images is to use a very thin emulsion. The images might, for instance, be made on a " whirled " coating of Lippman emulsion which is physically developed to give adequate density (Chapter 3). Another alternative is to restrict light spread and penetration into the emulsion by heavily dyeing the gelatin, and dyes suitable for this purpose have been investigated by Kowaliski.(2)

Execution of Resolution Tests

We have already noted that one needs to be certain that any deterioration of sharpness, which occurs when making a resolution test, is caused only by the component under test. This is not an easy condition to satisfy, and none of the methods which have been used are completely satisfactory. Results adequate for many purposes have, however, been obtained either by projection or by contact printing, and we shall consider these two basic methods separately.

Resolution Testing by Projection Printing

The resolution testing of lenses must necessarily always be done by projection. The lens under test is caused to form an image of a suitable chart, and this image is either examined visually with a microscope, or is recorded photographically. With visual examination of the aerial image, any vibration in the equipment is immediately apparent, and the change in image quality produced by changing the focus can be observed continuously. In recent years, however, it has been realized that a simple test of this type may give an unreliable indication of the photographic resolution likely to be obtained with a camera objective.(3) Inspection of the resolution given by an appropriate emulsion is therefore to be preferred, but this introduces the difficulty that a single photographic image cannot provide direct evidence that the focus was correct. The solution is to prepare a number of images at a series of focus positions so finely spaced that the difference of sharpness between adjacent images is only just apparent. The production of such a smoothly graduated focusing series demands an accuracy of registration and a control of focus well beyond the needs of ordinary photographic practice. Precautions similar to those needed in making microphotographs are, in fact, required, even when the results are recorded on a high-speed emulsion. The production of such a series, which shows a smoothly graduated improvement followed by a gradual deterioration, can be regarded as satisfactory evidence that the optimum resolution for the system has, indeed, been observed.

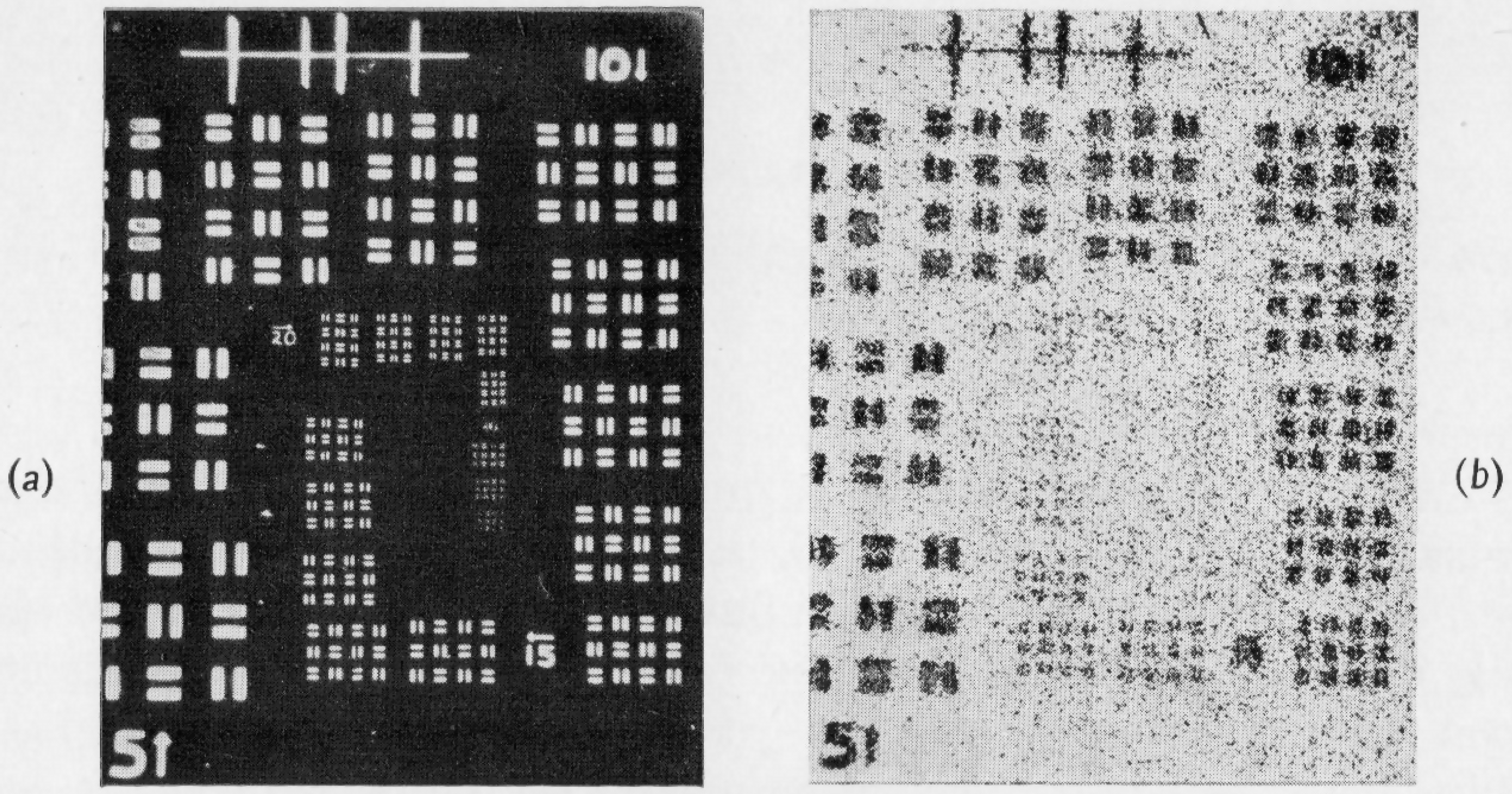


FIG. 75. *Resolution Testing by Contact Printing.*

(*a*) Test-chart image on Maximum Resolution plate (×40). The finest image corresponds to 200 lines/mm.

(*b*) Contact print on high-speed negative emulsion, clearly showing loss of resolution due to turbidity and graininess. (*See p. 282.*)

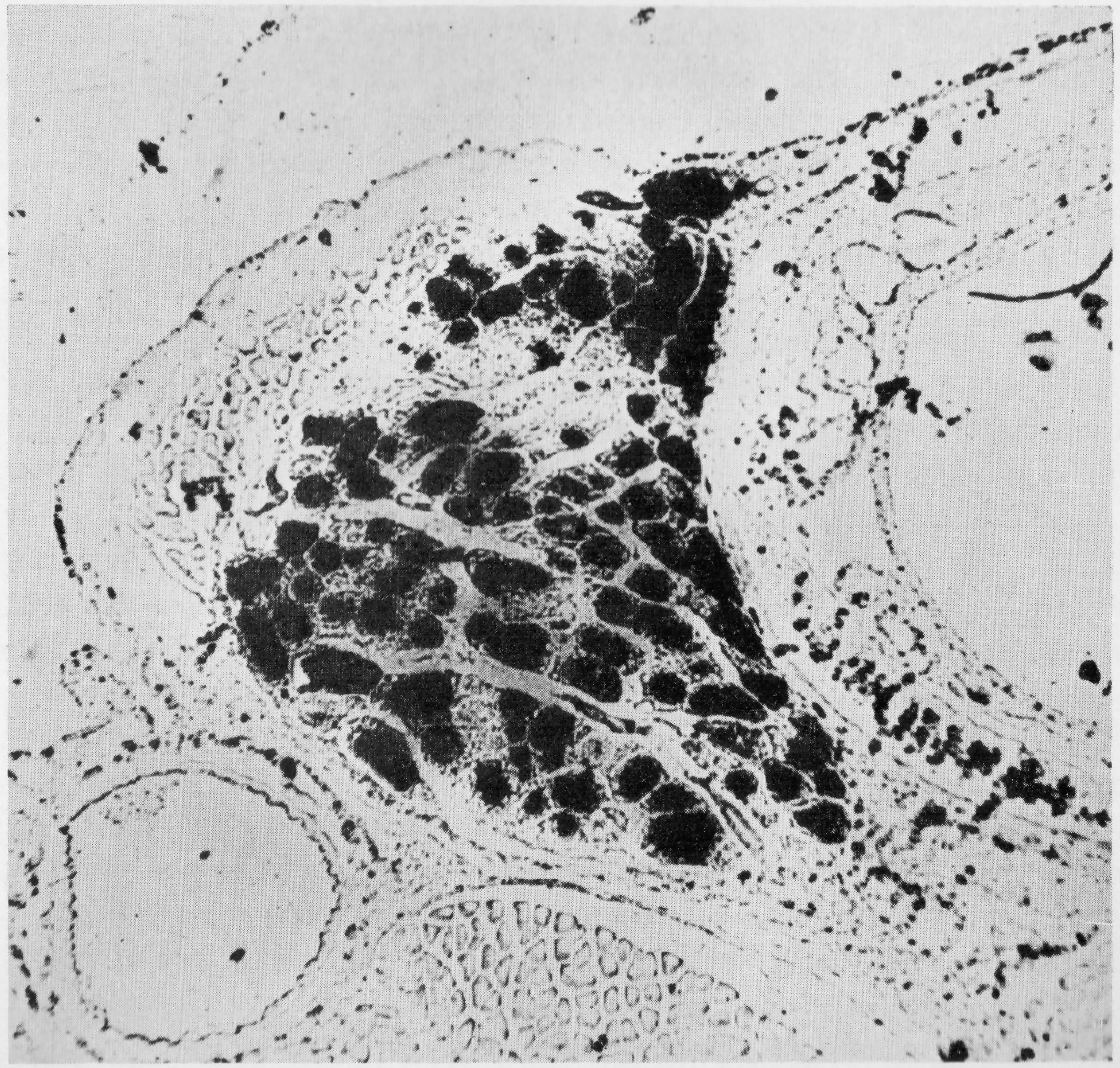


FIG. 76. *Tissue Section and Autoradiograph.*

Section (×35) from thyroid of rat injected with I^{131}. The outline of the unstained tissue only shows faintly, and certain restricted areas (mainly in the centre of the print) contained much radioactivity resulting in heavy blackening of the emulsion mounted on the section.

Courtesy of Dr. S. R. Pele.

[*Facing p. 280.*

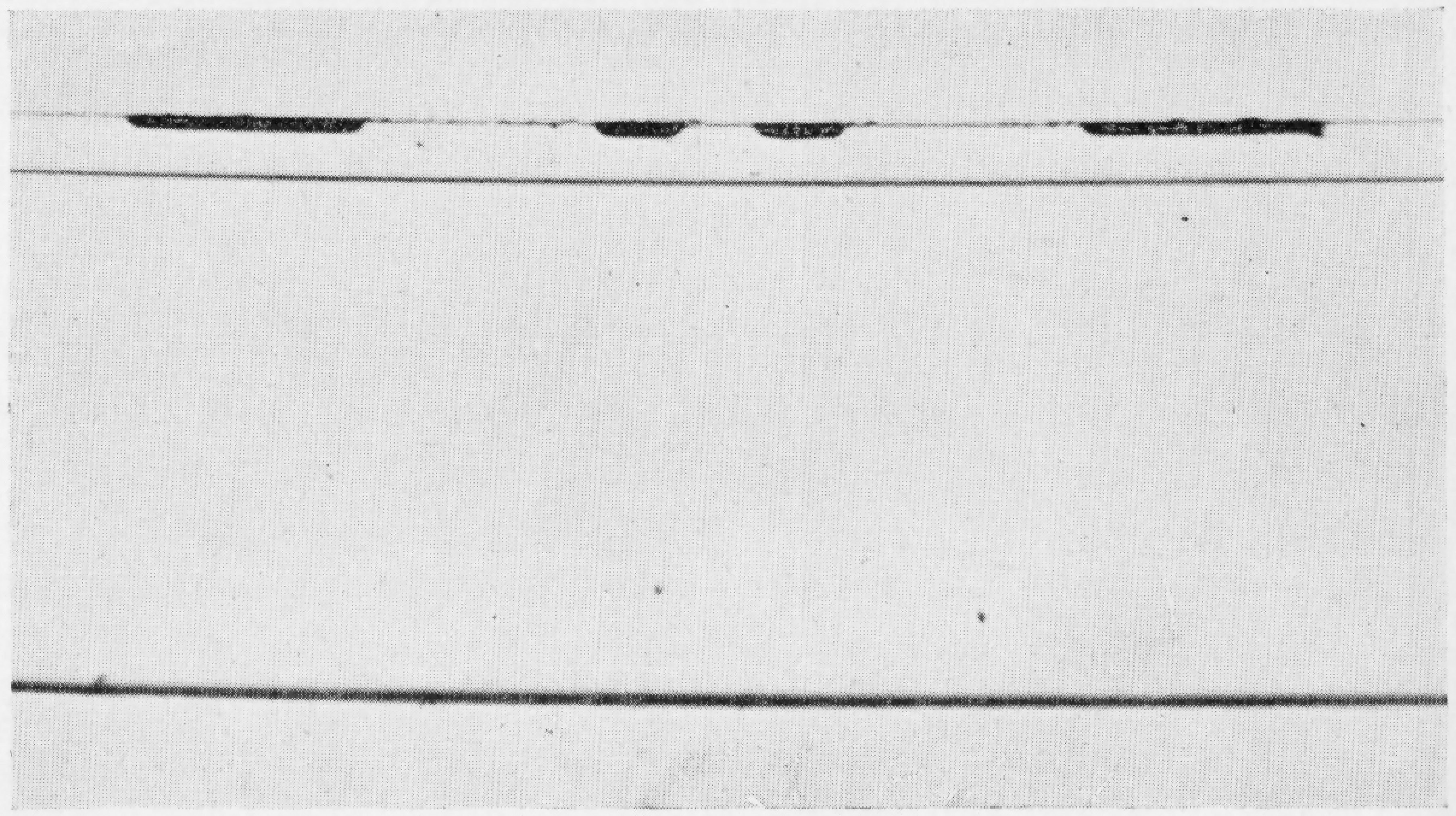
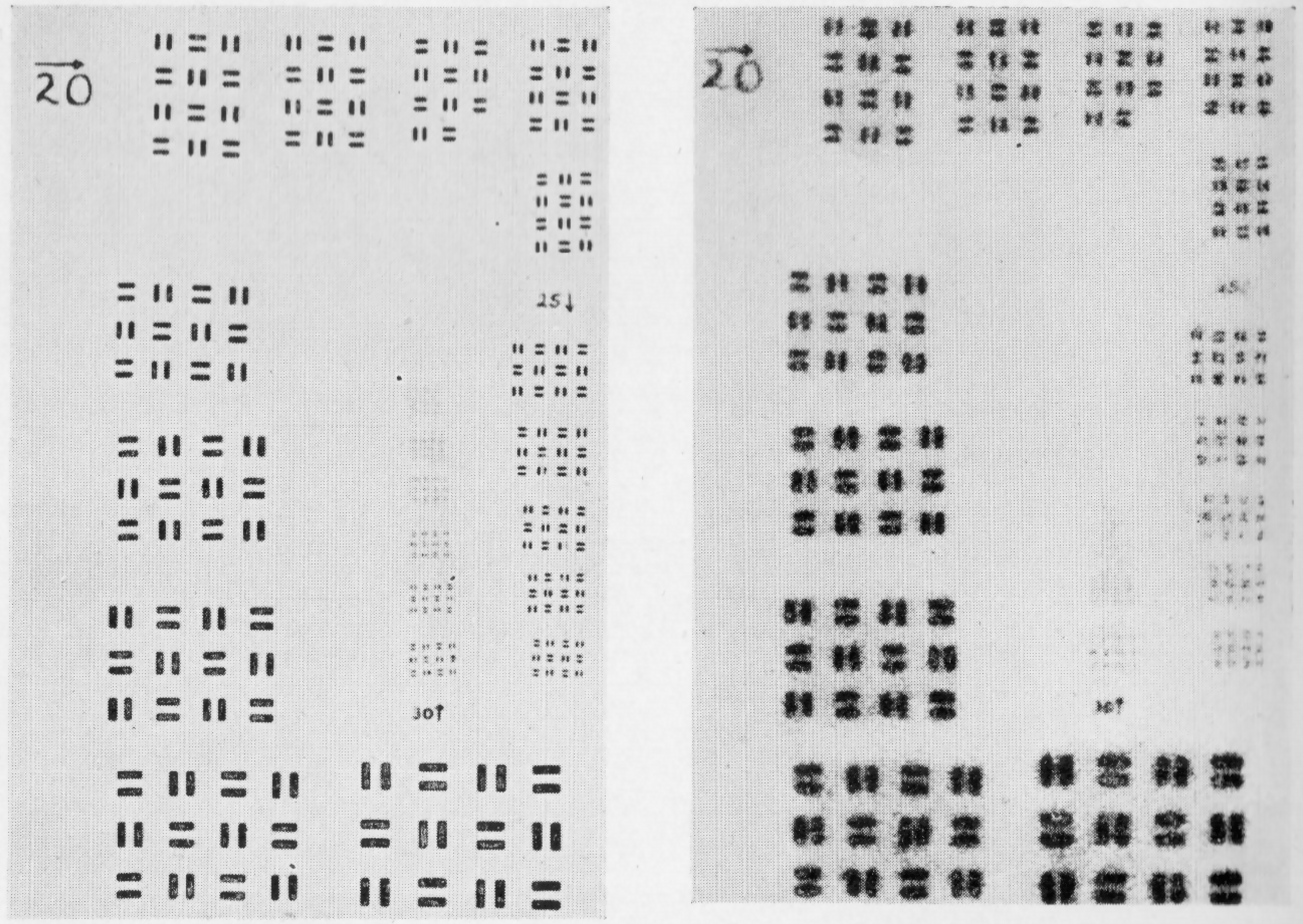


FIG. 77. *Section of Element of Test Image.*

Transverse section (×250) of emulsion with images confined to the surface.

Photomicrograph by courtesy of Miss J. Tabor. Kodak Research Laboratories, Harrow.

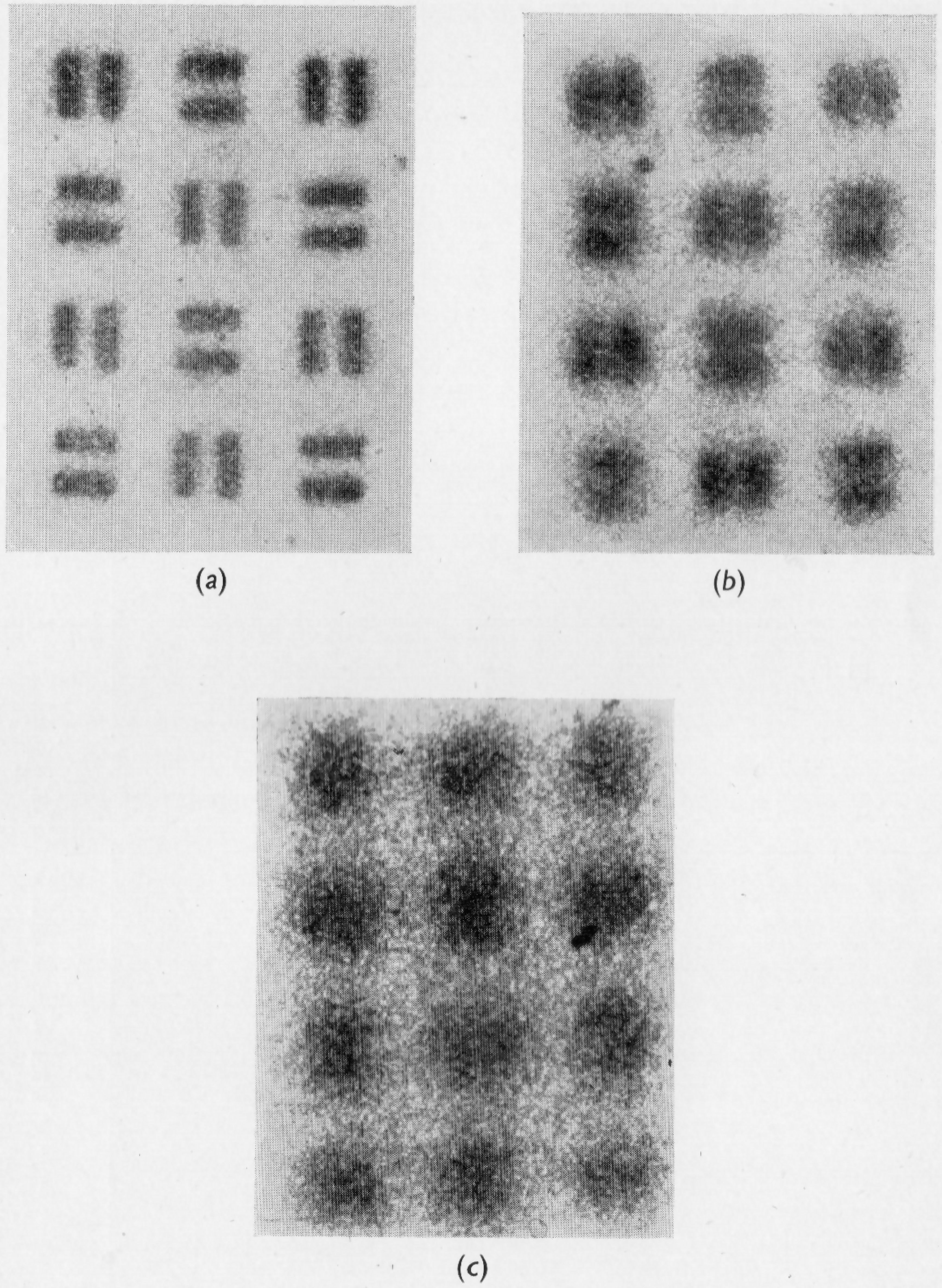


(a) (b)

FIG. 78. *Radioactive Test Chart, and Autoradiograph derived from it.*

(*a*) Photomicrograph (×150) of central portion of reduced test chart.

(*b*) Autoradiograph on nuclear-track stripping emulsion. Group 25 (corresponding to 215 lines/mm.) is still clearly resolved.



(a) (b) (c)

FIG. 79. *Effect of Separation on Sharpness of Autoradiograph.*

Photomicrograph (×250) of image corresponding to 56 lines/mm. (*a*) with perfect contact; (*b*) with 3 μ separation between emulsion and test chart; (*c*) with 10 μ separation.

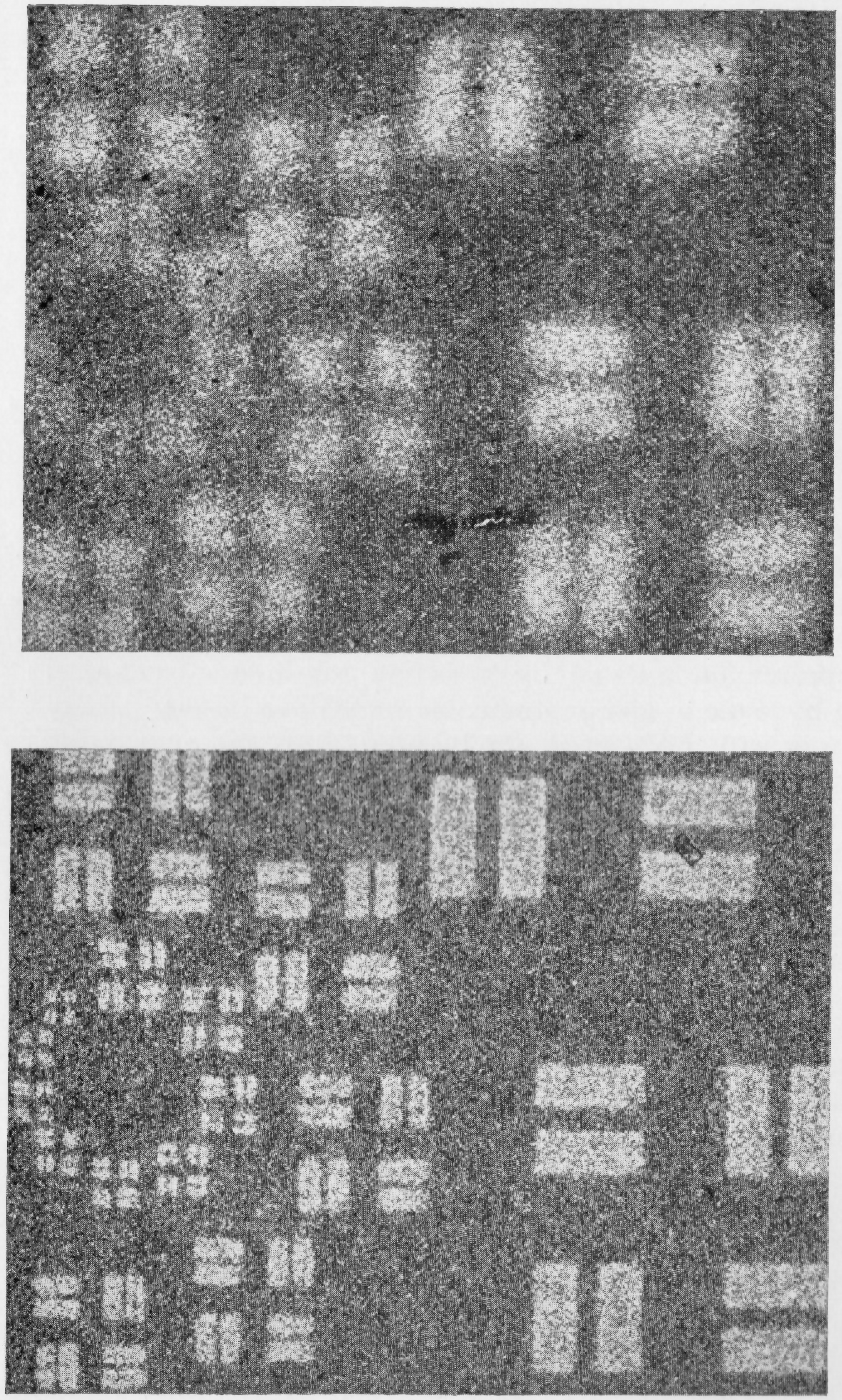


FIG. 80. *Resolution Test of Radiographic Process.*

(*a*) Photomicrograph (×50) from contact print on high-speed X-ray film exposed directly to 55 kV. X-rays.
(*b*) Image produced in the same conditions, but using intensifying screens.

This method of employing a finely-graduated focusing series to explore the change of resolution as the focus is carried through the focal plane, is the normal procedure for testing the photographic resolving power of objectives. The same method has also been used for measuring the resolution of photographic emulsions, in one published instance with the use of a microscope objective.(4) When a " perfect " lens is used for emulsion testing it is not necessary to make a separate focusing test on each emulsion. So long as the same narrow band of wavelengths is used for exposing all emulsions tested, it is only necessary to find the optimum focus with an emulsion of the highest possible resolution, and test all other emulsions at this setting. Microphotographic techniques are usefully employed at this stage. A reliable method for setting the focus is to make photographic focusing tests with a concentrated-Lippmann emulsion (Chapter 9), and this necessarily means that exceptionally precise methods for registration of the emulsion surface should be used (Chapter 6).

Emulsion-resolution testing by projection printing is a technique which can be made to give reproducible results over a long period of time, and with high-speed emulsions it gives the maximum resolution of which the emulsions are capable. The method is thus suitable for routine testing and production control. Measurement of the resolution limit of high-resolution, and particularly of microphotographic emulsions, is less simple, since the best available objectives may have a resolution limit comparable with that of the emulsion under test. The physical significance of emulsion-resolution figures obtained in these circumstances is uncertain, but the resolution test is still useful for making qualitative comparisons.

The most refined microphotographic technique is needed for the resolution testing of extreme-resolution emulsions, and the author employed a 4-mm. objective (N.A. 0·85) fitted with a distance piece, for testing " Kodak " Maximum Resolution plates (*Figure* 34). The same principle has been used by Perrin and Altman in a highly mechanized resolving-power camera capable of making these tests very rapidly.(5) Experience in emulsion-batch control of extreme-resolution emulsions has shown that tests made with equipment of this type provide a reliable means for detecting grain coarsening as a result of accidental ripening. The operation of this test by photographic manufacturers has been an important factor in the maintenance of the high standard of resolution of commercial concentrated-Lippmann emulsions.

Resolution Testing by Contact Printing

The resolution of high-speed photographic emulsions can conveniently be tested by exposing them in contact with a microphotographic test image, but this method has lost favour in recent years, since the test images soon become spoilt by scratching (*Figure* 59). Another objection is that the light distribution in the image at the emulsion surface is quite different from that obtained in normal usage, when the image is projected on the emulsion. Contact-resolution testing is, nevertheless, a useful method for the experimenter wishing to investigate emulsions or processing procedures without elaborate equipment, and has the advantage that the results cannot be confused by chromatic aberration of an objective.

A convenient method of performing a contact-resolution test is to use a row of identical microphotographic images. These are placed in a pressure printing-frame in front of a non-scattering optical wedge, so that the emulsion under test receives imprints of the test images at a series of intensity levels. In this way one exposure on a few square inches of film will allow the resolution at all points of the characteristic curve to be measured (*Figure* 75). The presence of dust between the test chart and the emulsion surface should be avoided, and with this precaution reasonably consistent results over a long period of time can be obtained on emulsions giving resolution figures up to 100 lines/mm. Perfect contact becomes increasingly important in the testing of emulsions of higher resolution ; and the tendency of dust and scratches to hold apart the surfaces of the test chart and emulsion has a more adverse effect. Tolerably consistent results have, with special care, been obtained up to 400 lines/mm., with the aid of an immersion fluid between the two surfaces to minimize the influence of refraction effects at the test-chart surface (Chapter 10). The mortality of the test charts is nevertheless high, and resolution testing by projection is undoubtedly the better method when a high resolution figure is expected.

Transformation Resolution Tests

Microphotographic images can be used to study the effects of

chemical modification or transformations of photographic images, and suitable transformations permit the images to be used for resolution testing in certain special applications of photography.

The effect of reducers or intensifiers or toning baths on the resolution of photographic images can be examined with great delicacy, by studying any change in the sharpness of microphotographic images in a concentrated-Lippmann emulsion. The observations, in the next section, on the effect of converting a silver image successively to silver bromide, and then to silver iodide and then to silver sulphide, are examples of this type of test. The same sort of procedure could be used to study colour development, which would appear to be a particularly interesting phenomenon to investigate ; since it is known that the production of the dye image is a secondary consequence of the formation of oxidized developing agent when an exposed emulsion grain develops. Study of the colour development of undeveloped test-chart images (or of developed images bleached to silver halide) could be used to establish how much migration of the dye image occurs, and its dependence on the couplers used, and on the composition of the developer. It is also probable that resolution-test images could, in the same way, prove useful in studying photomechanical and printing processes.

Chemical transformations of microphotographic test images have enabled objective estimates of resolving power to be made for autoradiography and X-ray radiography. The measurements in the former case could possibly not have been made by any other method. These two instances are worth considering in some detail, since they demonstrate the potentialities of microphotographic techniques in a way which may assist others to apply similar methods to their own problems.

Resolution Testing in Autoradiography

Autoradiography consists of the use of a photographic emulsion for detecting and studying the distribution of radioactivity in specimens of many different types. The radioactivity may be of natural occurrence (in minerals), but is more frequently present as a radioactive isotope employed in a " tracer " experiment. A frequently quoted example is the administration of radioactive iodine ($I^{(131)}$) to a rat, followed by autoradiography of sections of the thyroid gland to demonstrate the correlation between the distribution of the iodide taken up, and the histological structure of the gland (*Figure* 76). Experiments of this type are playing a considerable part in medical research. Such autoradiographs are often viewed with a microscope in the hope that it will be possible to demonstrate which group of tissue cells, or even what part of a cell contains the radioactivity. High resolution in the autoradiographs is thus of some importance. Much progress towards finding conditions conducive to high resolution has been obtained from theoretical calculations, but these inevitably contained many approximations, and experimental tests were also desirable. Estimates of resolution can be made by inspecting autoradiographs of biological specimens, but apart from its inconvenience, this method suffers from several intrinsic disadvantages. For this purpose histological sections must be considered as three-dimensional objects, with the radioactivity distributed at all levels inside the thickness of the section. In addition, the distribution of radioactivity is never likely to be the same in two sections, even when cut from the same specimen ; and the distribution is anyhow unknown. It must, therefore, be concluded that examination of histological autoradiographs does not offer an ideal basis for systematic tests.

Now developed photographic images can be submitted to a variety of chemical transformations, many of them leading to the deposition of elements of which radioactive isotopes are readily available. It therefore seemed possible that a suitable toning procedure could be used to make resolution-test images radioactive. Iodine was chosen since the $I^{(131)}$ isotope emits beta particles suitable for autoradiography, with a convenient half-life of eight days. The images were converted by bleaching them first to silver bromide, which was then allowed to react with the iodide :

$$\begin{aligned} Ag + KBr + K_3Fe(CN)_6 &\rightarrow AgBr + K_4Fe(CN)_6 \\ AgBr + NaI &\rightarrow AgI + KBr \end{aligned}$$

Preliminary experiments had shown that a microphotographic test image could be successively converted from silver to silver bromide, and then to silver iodide and silver sulphide, and yet still resolve more than 1,000 lines per millimetre.⁽⁶⁾ This provided good evidence that the distribution of the silver iodide, and hence the distribution of the radioactivity, must have followed the silver in the image quite faithfully.

The images actually used in the resolution tests were made on Maximum Resolution emulsion which had been heavily dyed to restrict light penetration.⁽⁷⁾ As already explained, this both permitted a wide range of image sizes to be reproduced satisfactorily and confined the images to the very surface of the emulsion (*Figure* 77). Now it is known that good resolution in autoradiography depends on securing the smallest possible separation between the radioactive specimen and the photographic emulsion, and these test charts were equivalent to the most favourable histological section with all its radioactivity concentrated in the surface. After the test charts had been converted to silver iodide, and washed thoroughly to remove unreacted sodium iodide from the gelatin, various stripped emulsion layers were applied by Pelc's technique.⁽⁸⁾

A piece of dry photographic emulsion stripped from a specially prepared plate is laid on a clean water surface. The emulsion first tends to " pucker ", but within a minute or so stretches out quite flat on the water surface.⁽⁹⁾ It can then be lifted out on the slide bearing the tissue section or test chart, and on drying down follows all the undulations of the specimen, so that substantially perfect contact is achieved. The emulsion is then stored in the dark until sufficient grains are fogged by the radioactivity (usually several hours or days), and in the normal way the autoradiographs are developed while still attached to the tissue section. This permits the investigator to compare the autoradiograph with the tissue simply by racking the microscope up and down. For resolution testing, however, it seemed better to remove the autoradiographic emulsion before processing, so that no physical development of the test-chart image could occur.

This testing method was used to investigate the influence of emulsion-type and coating-thickness on resolution, and the experiments led to the conclusion that a four-micron layer of a nuclear-track emulsion should give the optimum results. *Figure* 78 shows the resolution obtained on " Kodak " autoradiographic plates as a result of this work. The effect of separation between the specimen and emulsion was also investigated by super-coating the test-chart images with a clear gelatin solution. The thickness was adjusted by spreading a definite volume of solution over a measured area of the plates bearing the images, which were laid on a level slab to ensure a uniform coating. Industrial experience in the coating of plates shows that the thickness can be accurately calculated from the weight of gelatin per unit area. *Figure* 79 shows that a 3-μ (0·0001-in.) separation seriously decreased the sharpness of the autoradiographs, while 10-μ (0·0004-in.) separation resulted in gross blurring of the images.

Resolution Testing in Radiography

The penetrating property of X-rays makes it difficult to obtain test objects which are opaque enough to give a radiograph with useful contrast, but have sufficiently fine structure to allow the limit of resolution to be measured. Bones or wire meshes or similar structures are useful for making direct comparisons, but are less satisfactory for scientific work. It has been found that photographic images with the properties necessary for some tests can be prepared from concentrated-Lippmann plates.(10) We have already seen that the chemically-developed image in materials of this type consists of a finely divided silver deposit, whose mass can be greatly increased by physical development (Chapter 3). This increase in mass by itself raises the opacity of the image to X-rays, but a further substantial increase can be obtained by depositing a metal of higher atomic number than silver. Physical development in a formula due to Lumière and Seyewetz (11) allows mercury (atomic number 80) to be deposited in the same way as silver (atomic number 47) is deposited from more conventional physical developers. When this process was continued for several hours with hourly renewal of the solution and constant agitation, the thickness of the images was found to correspond to 0·001 in. (25 μ) of liquid mercury. This was several times the thickness of the original emulsion layer, and the mercury was chemically equivalent to fifty times the total silver content of the coated emulsion layer.

Test images prepared by mercury physical intensification of resolution charts on Maximum Resolution plates were very satisfactory in some conditions, but only partly satisfactory in others. This was due to the operation of two factors. In the first place the opacity of any given image decreases with increasing kilovoltage and greater penetrating power of the X-rays, and a correspondingly heavier deposit is needed to produce any required opacity. The second factor is the image spread resulting from the deposition of a mass of metal having several times the thickness of the original emulsion. It was, therefore, decided to employ the minimum degree of intensification needed to give a useful visible contrast on the radiograph in any particular test. Although this expedient was used to circumvent experimental difficulties, it did not make the tests unrealistic, since most of the lesions or faults detected on medical or industrial radiographs give rise to low-contrast images.

This method gave the following results. A short intensification produced test charts having an opacity of 4 to the soft X-rays (8 kV.) used for microradiography, and showing satisfactory resolution down to the last group (320 lines/mm.). Tests on different emulsions in these conditions showed that the resolution limit could easily be measured on commercially coated X-ray film and on a photomechanical film, but a fine-grain nuclear-particle emulsion resolved the last group. This chart was thus useful for measuring the resolution of emulsions intended for making microradiographs to be viewed at moderate magnifications (50 diameters), and could be considered to have achieved a limited, but useful, objective. Any attempt to make test images capable of measuring the resolution of concentrated-Lippmann emulsions would, however, almost certainly fail. This is because the resolution of all emulsions exposed to soft X-rays is equal to or higher than their resolution to light; which precludes the possibility of forming sufficiently fine images for this purpose by optical projection.

Tests were also made with heavily-intensified images for use with harder X-rays, and these test charts had an opacity of 1·5 to radiation of the quality acting on the emulsion in chest radiography (55 kV. with 0·2 mm. copper filtration). Now two entirely different standards of resolution can be achieved according to the exposure conditions used for medical radiography. When the highest possible speed is required, the film is exposed between intensifying screens, which raise the effective emulsion speed but reduce the resolution to 10–20 lines/mm. The same emulsions exposed to direct X-rays may record well over 50 lines/mm. The heavily-intensified test charts were found to be quite fine enough for measuring the resolution limit obtained with intensifying screens, but not for exposure to direct X-rays (*Figure* 80). It could, in fact, be fairly claimed that the range of resolution tests suitable for radiography had been extended by the use of microphotography, even if the usefulness of the method was restricted by experimental difficulties.

Investigation of the " Fine Structure " of Optical and Physical Processes

The properties of microphotographic emulsions enable them to record processes which it would be difficult or impossible to observe in any other way, or to reveal the " fine structure " of physical phenomena or technical processes. The scope of this method will be evident from the examples discussed below.

Recording of Standing Light Waves

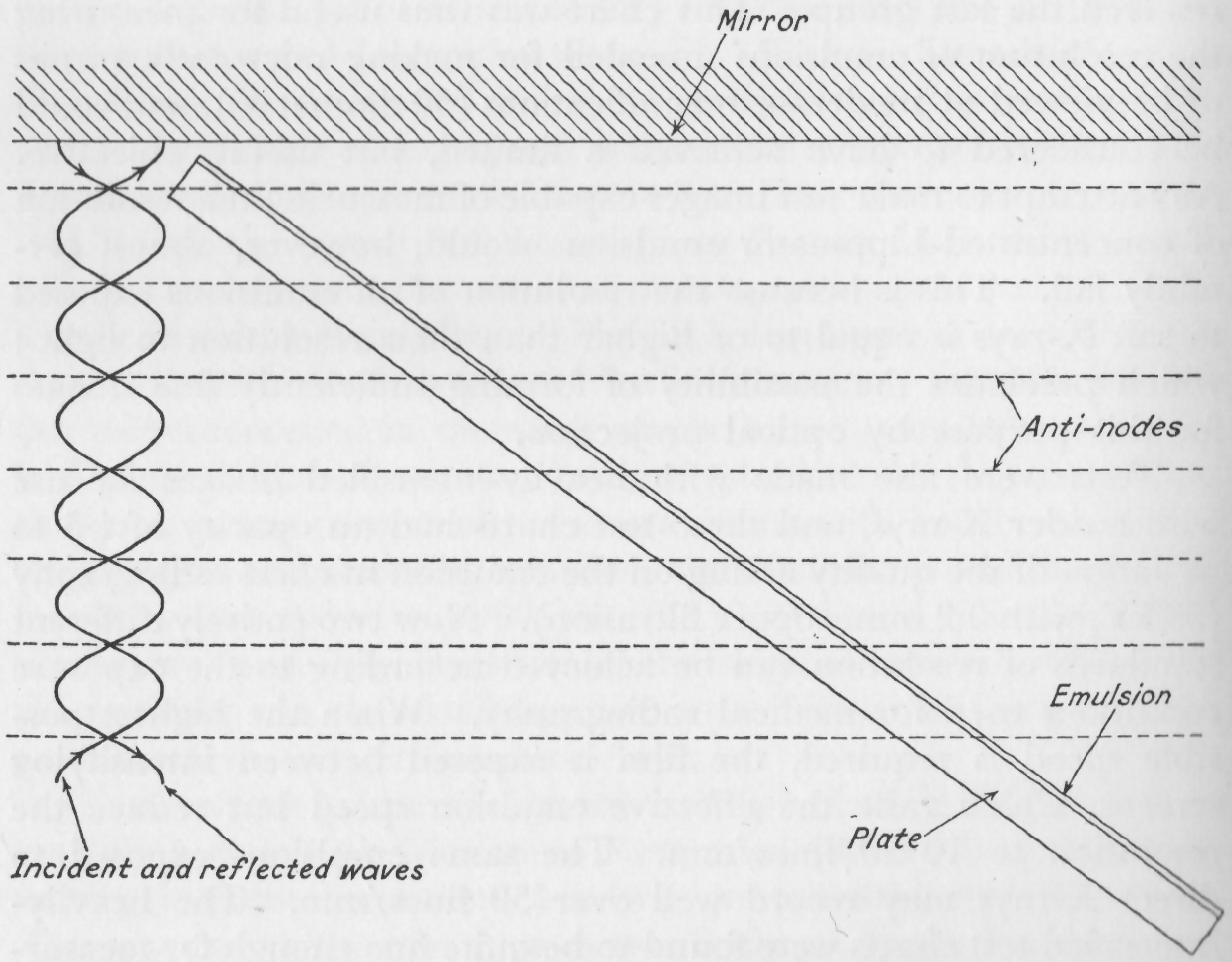


FIG. 81*a*. *Recording of Stationary Light Waves.*

Wiener's experiment. A very thin transparent emulsion was placed at an angle close to a mirror.

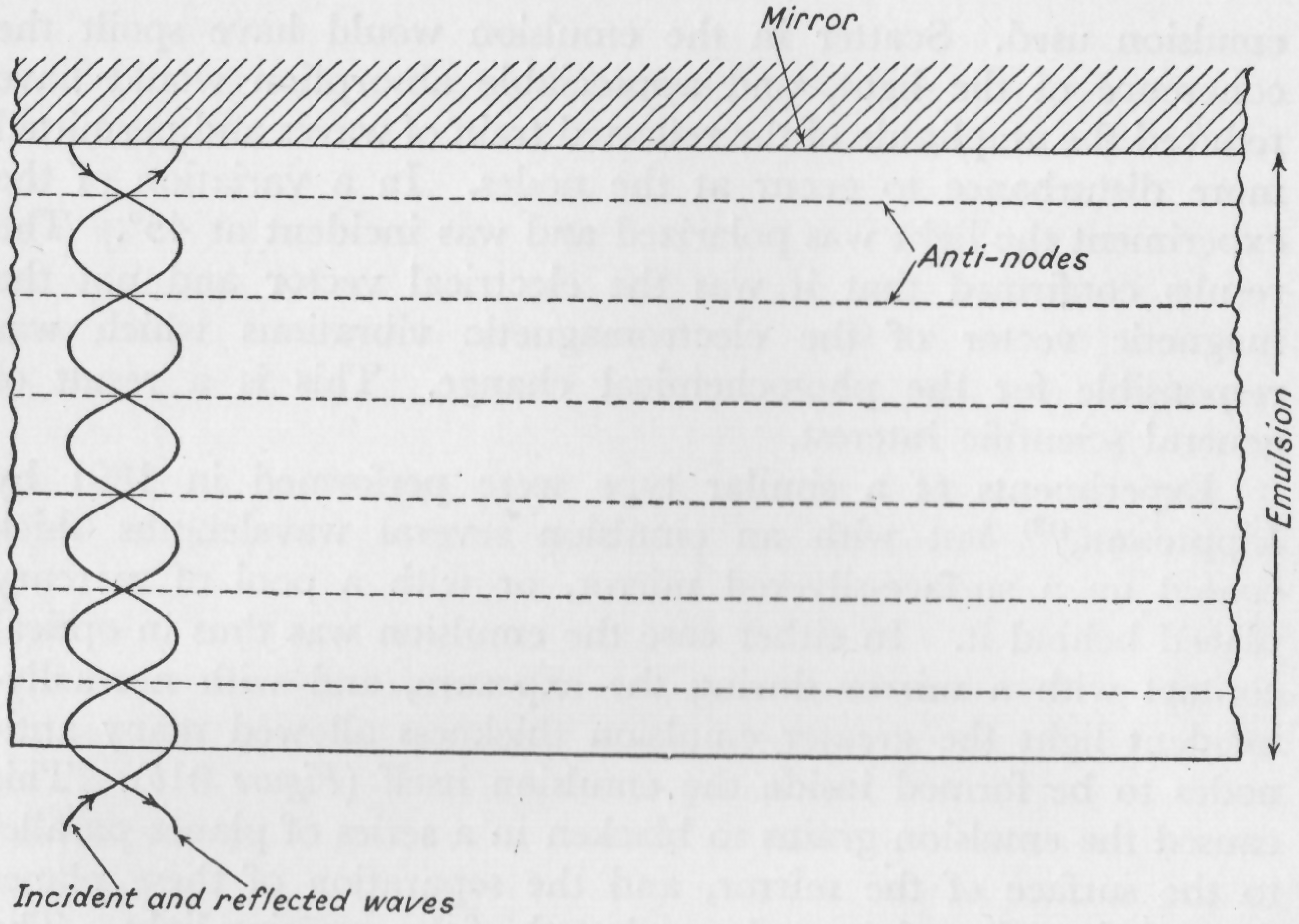


FIG. 81*b*. *Recording of Stationary Light Waves.*

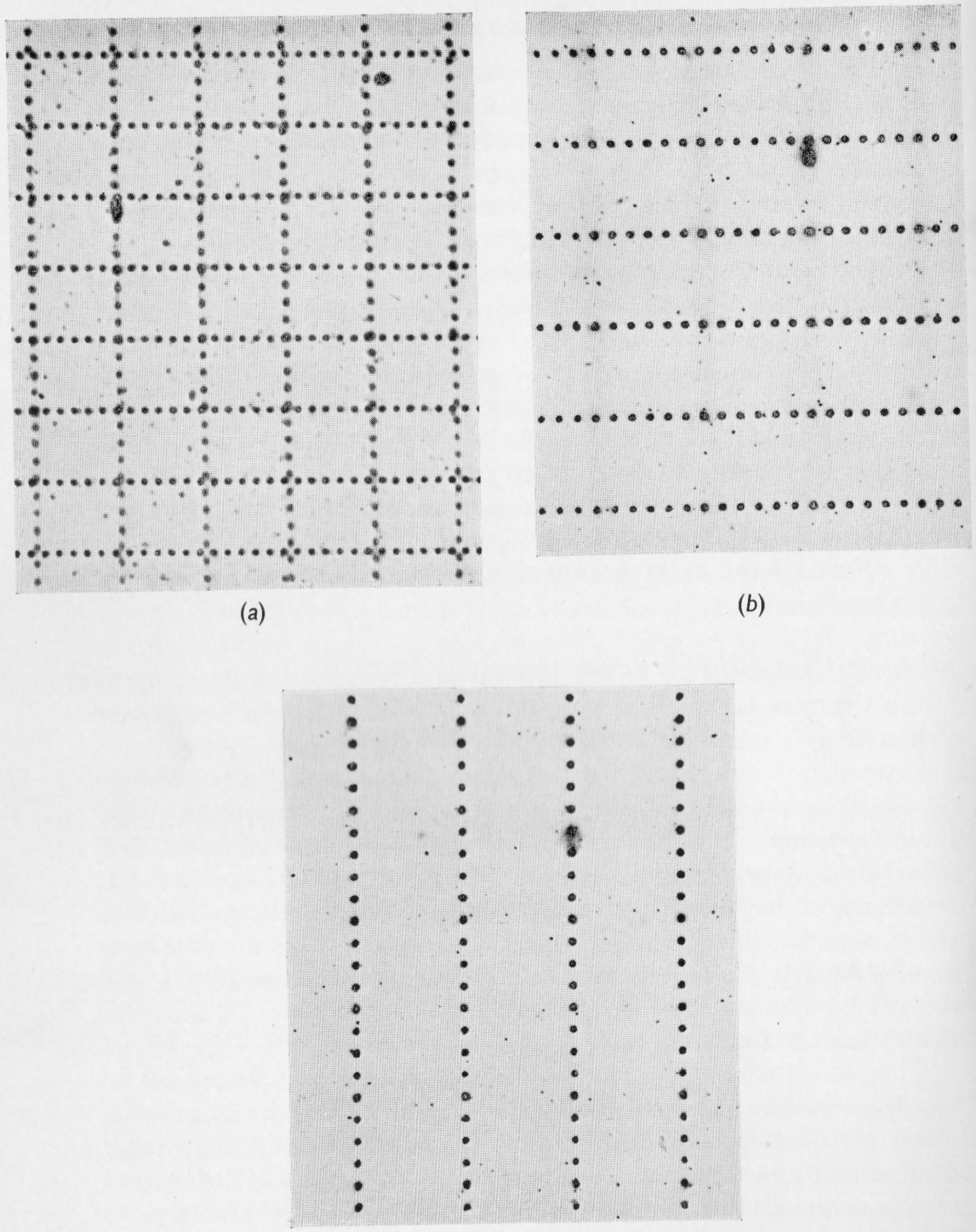
Lippmann's process of colour photography. A relatively thick layer of very transparent emulsion was placed in optical contact with a mirror.

When a series of waves is reflected by a suitable surface, interference occurs between the incident and reflected waves. In the simple case of straight waves parallel to and moving towards a straight reflector, interference causes the establishment of a system of stationary bands of maximum disturbance (anti-nodes) and minimum disturbance (nodes). The nodes and anti-nodes are parallel to the reflector, and successive nodes are separated by half the wavelength of the waves. Such waves are known as *stationary* or *standing waves*, and can be easily observed in water waves. They should also be formed when light is reflected from a mirror, and in 1890 Wiener demonstrated their existence with a microphotographic emulsion.(12) The emulsion surface of plates coated with a thin layer corresponding to only a twentieth of the wavelength of light was placed very close to, and at a small angle from, a surface-silvered mirror (*Figure* 81*a*). After exposure to normally-incident light, the plates on development were found to be blackened in narrow parallel lines, corresponding to the zones where the emulsion intersected the anti-nodes. The success of this experiment was due to the high resolution, low absorption and low scatter of the emulsion used. Scatter in the emulsion would have spoilt the coherence of the light, and appreciable absorption would have reduced the amplitude of the reflected train of waves and permitted more disturbance to occur at the nodes. In a variation of the experiment the light was polarized and was incident at 45°. The results confirmed that it was the electrical vector and not the magnetic vector of the electromagnetic vibrations which was responsible for the photochemical change. This is a result of general scientific interest.

Experiments of a similar type were performed in 1891 by Lippmann,(13) but with an emulsion several wavelengths thick coated on a surface-silvered mirror, or with a pool of mercury placed behind it. In either case the emulsion was thus in optical contact with a mirror during the exposure, and with normally-incident light the greater emulsion thickness allowed many anti-nodes to be formed inside the emulsion itself (*Figure* 81*b*). This caused the emulsion grains to blacken in a series of planes parallel to the surface of the mirror, and the separation of these planes depended on the colour and wavelength of the exposing light. The developed emulsion layer thus contained a periodic structure which, under appropriate viewing conditions, selectively transmitted or reflected the wavelengths which had produced the structure. This was the basis of Lippmann's process of colour photography.

Lippmann's experiment made even greater demands on the emulsion used. The increased thickness of the layer meant that the transparency and clarity of the emulsion needed to be even more perfect than in Wiener's experiment. Moreover, in Wiener's work the separation of the images of the anti-nodes was greatly increased by inclining the emulsion at a small angle from the mirror, whereas in Lippmann's process the emulsion had to record the separation of successive fringes formed within its own depth. When allowance is made for the refractive index of the emulsion, the recording of blue light of wavelength 4,500 Å. corresponds to a line width of 0·000003 in. (0·075 μ), or a resolution of about 6,000 lines/mm. Such photographs, in fact, probably display the highest photographic resolution which has ever been achieved.

Another interesting feature of Lippmann's colour photographs is that they constitute a three-dimensional record of the disturbance in the aether at the time of exposure. In this respect, therefore,



(a) (b)

(c)

Fig. 82. *Separate Images in the Upper and Lower Layers of the Same Emulsion.*

The images were produced by giving two exposures at different focus settings, with the negative turned through a right angle for the second exposure.

(*a*) Photomicrograph (×720) with objective stopped down to show both images.

(*b*) Horizontal lines and blemish in emulsion surface. (×900.)

(*c*) Vertical lines in emulsion depth, lying just underneath blemish. (×900.)

[*Facing p.* 291.

they can be said to be truly three-dimensional photographs, which can be contrasted with stereo pairs giving the *illusion* of three dimensions when viewed under appropriate conditions. The ability to provide three-dimensional records in a single layer is derived from the optical clarity of the emulsion, which permits almost equally sharp images to be formed at all levels in the emulsion, and from its low absorption which allows grains at all levels to receive almost the same exposure. The microphotographic processes using silver salts mostly have the low absorption necessary for this type of application, but certain other emulsions (such as the diazo materials) absorb too strongly to be used for this purpose.

A recent example of this three-dimensional property has been provided by Wolfe and Eisen, who recorded Lloyd's fringes in an Eastman 548 G.H. plate. Sections cut through the processed emulsion confirmed that the images of the fringes consisted of thin vertical laminae of grains passing through the depth of the emulsion.(14)

Recording the Light Distribution in Optical Images

In Chapter 10, dealing with anomalous image formation, it was shown that concentrated-Lippmann emulsions are capable of recording the " fine structure " of image formation, in a way which would be impossible on faster emulsions of lower resolution. All three cases quoted had the common feature that the images departed from ideal reproductions of the original transparencies, and the revelation of the fine structure was of great assistance in interpreting the reasons for the defects. Thus the formation of a third line from a two-line test chart was ascribed to the lenticular surface of the negative, and extraordinary spikes on a contact print of a graticule were traced to interference of light from adjacent parts of the image.

The third case, in which a spurious image was found in the emulsion surface, when the image of a grating was focused in the lower emulsion layers, suggests that the possibility of forming such three-dimensional records could be of value in optical research.

An even clearer demonstration of the ability of this type of emulsion to record " optical sectioning " is shown in *Figure* 82. A negative containing rows of dots was projected into the emulsion surface and one exposure made. The objective was then re-focused so that the images were formed at the bottom of the emulsion, and a second exposure was made with the negative turned through a right angle. *Figure* 82 shows that both images were recorded quite separately within the 0·0002-in. (5-μ) depth of the emulsion. This technique might be used for making test objects designed to illustrate the depth of focus of microscope objectives.

Emulsion properties which enable images like this to be obtained could be used in other ways. The field curvature in the image plane of microscope objectives, on their own or with suitable oculars, could be measured by projecting a reduced image of a negative with rows of dots into a microphotographic emulsion. A transverse section of the resultant developed image should permit the field curvature to be observed directly, and to be measured with fair precision. The usefulness of this method might also be extended by employing thicker emulsion coatings, with the necessary transparency preserved by the use of lower silver concentrations combined with the ultra-fine grain of a true Lippmann emulsion (Chapter 3). Knowledge about the processing of thick emulsion layers obtained in nuclear research suggests that coatings of thicknesses of 0·004 in. (100 μ), or more, could be used for this purpose. Such a depth is sufficient to record the changes of light distribution for a useful distance on either side of the focal plane, even with objectives of quite moderate aperture.

The " Fine Structure " of Mechanical Phenomena

Details of the movements of metal during the fabrication of different shapes have been studied by imprinting a fine grid of lines on the metal, and observing the distortions produced during manufacture. The resolution obtainable by use of extreme-resolution emulsions enables this method to be operated on a greatly reduced scale ; and its potentialities have been illustrated by an investigation of the glazing of photographic prints.(15)

When allowed to dry with the emulsion open to the air, the surface of prints on " glossy " photographic papers have a definite texture which causes the emulsion to give a somewhat diffuse rather than specular reflection of light. If prints on the same papers, however, are allowed to dry with the emulsion pressed into contact with a highly-polished surface, the dried emulsion becomes glass-smooth and reflects light specularly. It seemed likely that the details of this glazing process could be studied by observing the

behaviour of a sufficiently fine grid printed on paper coated with an extreme-resolution emulsion. For this purpose Maximum Resolution emulsion was used heavily dyed to prevent halation from spoiling the definition (Chapter 3), and was coated at the thickness and with the hardeners normally used for paper emulsions. The images were obtained by direct projection, using a $\frac{2}{3}$-in. (16-mm.) achromat with a " salt-cellar " distance piece (*Figure* 34). The resultant grid had lines about 0·0001 in. (2–4 μ) wide and 0·0005 in. (12 μ) apart, with satisfactory sharpness over a circle of 0·04 in. (1 mm.) diameter.

When these images were dried open to the air, the lines showed hardly any distortion, even when the underlying structure of the paper showed that the emulsion surface must have been quite uneven (*Figure* 83*a*). Similar prints cold-glazed by drying in contact with a ferrotype sheet, or hot-glazed on a commercial glazing machine, showed definite distortion of the grid. The size of the emulsion shifts varied greatly over the surface of the prints, being greatest over prominent paper fibres (*Figure* 83*b*), but no significant difference between hot-glazed and cold-glazed prints could be detected. In the worst cases the distortion corresponded to about half a division of the grid (0·00025 in., or 6 μ), which is small compared with the least separation (about 0·002 in. or 50 μ) which can be seen by the naked eye. Such small distortions of the emulsion are thus unlikely to influence the image sharpness of ordinary photographic prints.

The reason for these distortions can be deduced from a detailed consideration of the nature of the glazing process. The surface of a freshly processed and wet print is quite rough, and can be likened to mountainous country with hills and valleys. When the wet emulsion is applied to the glazing surface, air and the gross excess of water are removed by a roller or a squeegee. At this stage only the hills can actually be touching the glazing surface, and the valleys must still be filled with water (*Figure* 84). Now the glazing sheet is quite impervious, and the emulsion can, therefore, only dry as a result of water evaporating through the paper base. It obviously will not be dry until all the water filling the valleys has also evaporated. Forces exerted during this stage of the drying must be sufficient to draw the floors of the valleys in the still plastic emulsion layer right up to the glazing surface. The final stages

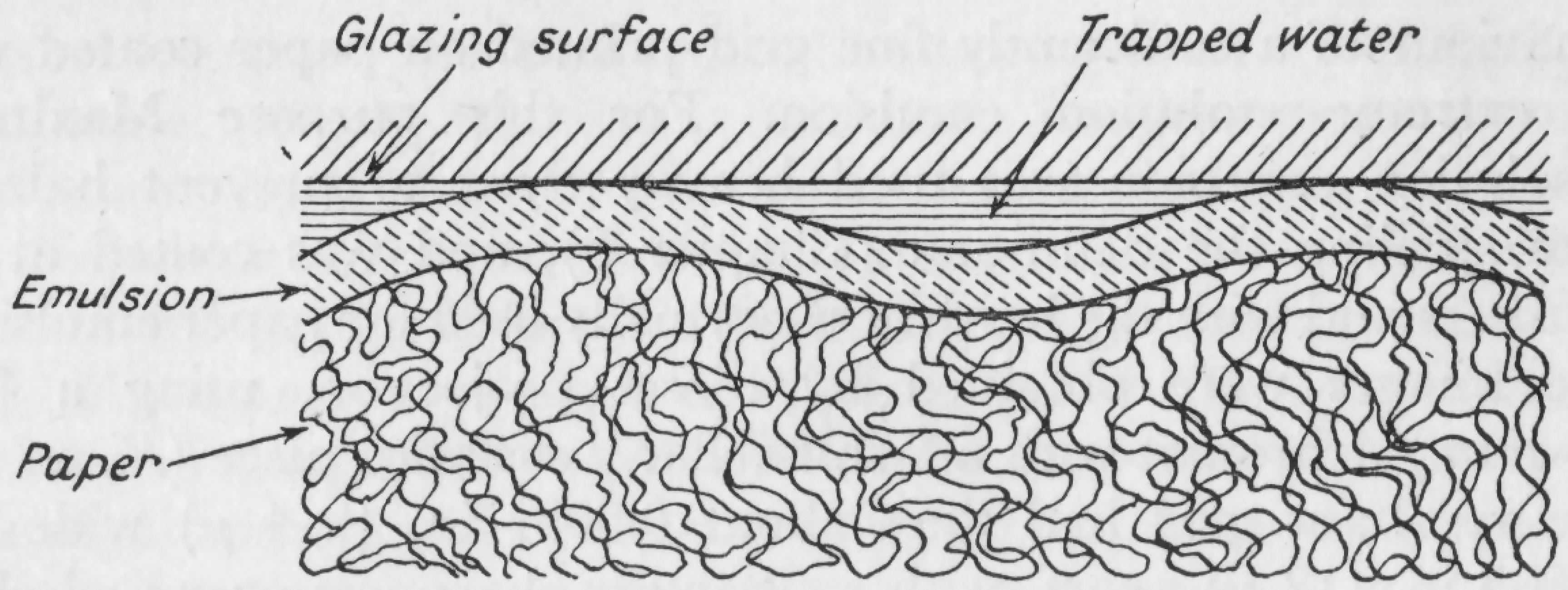


FIG. 84. *Wet Paper Emulsion before Glazing.*

When the emulsion is squeegeed to the glazing surface, pockets of water are trapped in the hollows of the emulsion surface.

of drying then take place with the whole emulsion surface in practically molecular contact with the glazing sheet, so that the emulsion acquires the polished finish of the glazing surface. It is thus evident that different areas of the emulsion surface must suffer vertical movements relative to each other, and it is most probable that these vertical movements will be accompanied by lateral shifts. On this hypothesis the lateral distortions are likely to be greatest where the emulsion surface is most uneven, and the correspondence between the largest lateral shifts and prominent paper fibres is thus only to be expected.

It would be idle to claim that this experiment on glazing is of any great intrinsic importance, or that it is likely to facilitate important technical advances. The feature of general interest, however, is the demonstration of an investigational technique which almost certainly has other applications. It could, for instance, be used to study the fine detail of the movements of metal in the striking of coins, and its relation to the structure of the metal and the speed and pressures developed by the press.

Research Techniques allied to Microphotography

This chapter would be incomplete without reference to other photographic research techniques which are closely allied to microphotography. These are *microradiography*, *autoradiography* and the use of *nuclear-particle* emulsions for studying nuclear transformations.

In microradiography a microphotographic emulsion (concentrated-Lippmann emulsions are often used) is exposed in intimate

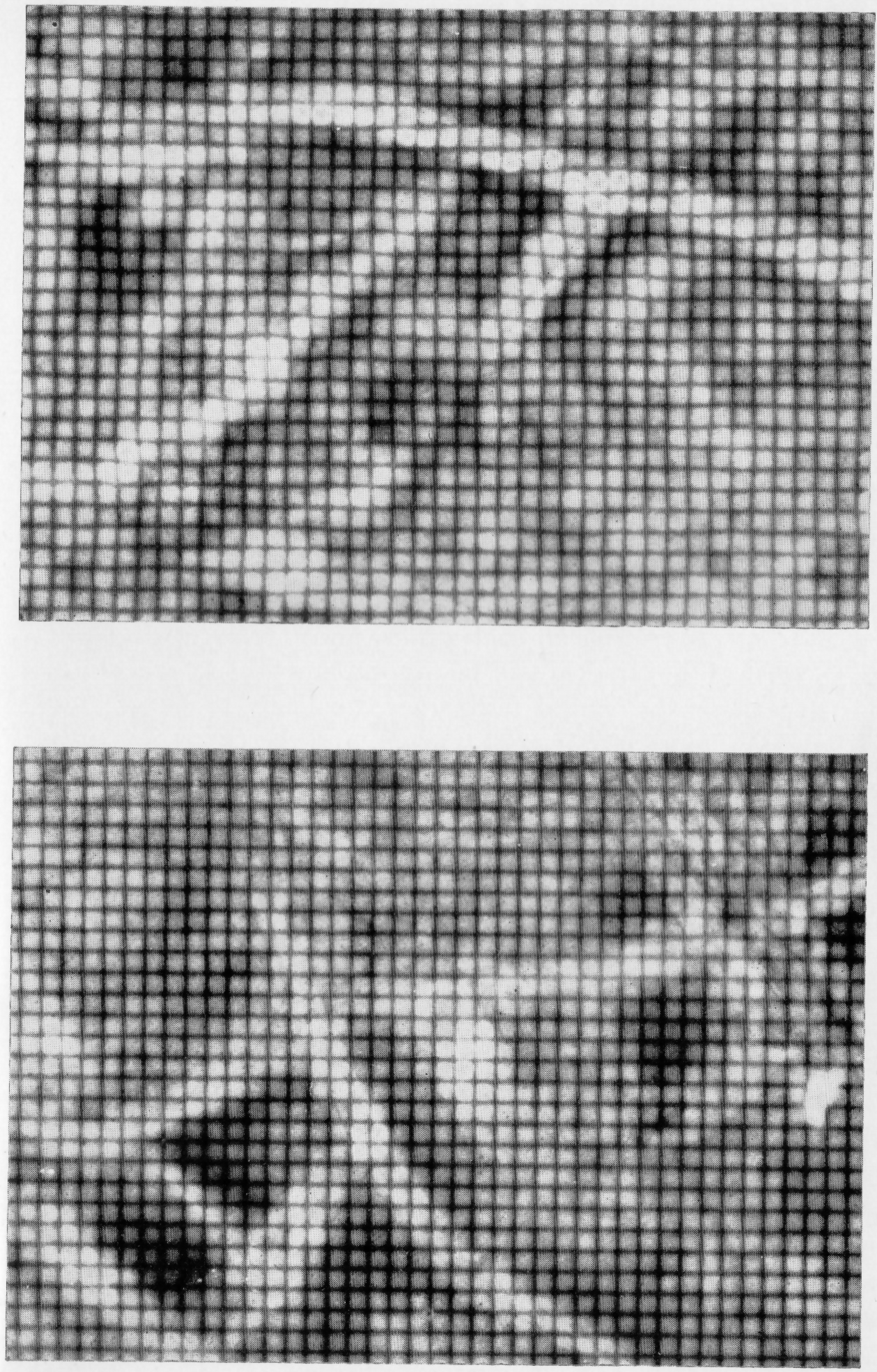


FIG. 83. *Image Shifts produced by Glazing of Prints.*

(*a*) Photomicrograph (×200) of grid image on paper sensitized with heavily dyed Maximum Resolution emulsion.
(*b*) Distortion in grid produced by glazing. Note how the largest shifts follow strong paper fibres.

contact with a thin specimen to a nearly-parallel beam of soft X-rays. This technique gives radiographs which can then be enlarged optically a hundred diameters or more. The method was devised because of the difficulty of refracting or reflecting X-rays, and thus obtaining the magnification directly by optical manipulation of the X-rays themselves. Advantages compared with optical microscopy are the ability to study the internal structure of opaque specimens (such as insects, rocks and metals) ; and since the absorption of X-rays depends only on the atomic composition of the specimen, and not on the structure of constituent molecules, further valuable information can be obtained from studying radiographs. Additional information can be obtained by the injection of " contrast media " (e.g. lead, gold or iodine compounds) into biological specimens, and the use of X-ray wavelengths selectively absorbed as a result of resonance by one constituent in a metal or rock. It is not clear how long this simple " contact " method will continue to be used in view of a technique developed by Cosslett,(16) which uses a minute focal spot and obtains a magnified shadowgraph by placing the specimen close to, and the film at some distance from, the source. Each technique may prove to have its own advantages, and continue to be used according to the requirements of the work and the equipment available.

Autoradiography has already been discussed in connection with resolution testing. High-resolution autoradiography consists essentially in the use of an emulsion of such fine grain that the autoradiograph will be suitable for inspection under the microscope. The autoradiograph is, in fact, a " microphotograph ", but extreme-resolution emulsions (as defined in Chapter 3) are not needed for their production.(7) This is because of the resolution limit set by the wide angle of the radiation entering the emulsion. So far no advantage in resolution has been obtained by the use of emulsions with average grain diameters below 0·2 μ, whereas the loss of speed consequent on the use of even finer grain sizes may necessitate the use of an undesirably high concentration of radioactive isotope.

When studying the nature of atomic disintegrations the nuclear physicist needs to know the angles and velocities at which the disintegration particles are given off. He then equates the momentum of the reaction products and of the particles whose collisions produced the reaction, and from this calculates the probable masses of the reaction products. Until 1945 the necessary detailed information about these nuclear transformations depended largely on the use of the Wilson cloud chamber. In this apparatus dust-free air is expanded adiabatically and becomes supersaturated with water-vapour. Ionization of the air by the passage of charged nuclear particles produces nuclei on which water can condense, and a photograph taken shortly afterwards reveals the track of the particles as a chain of minute water droplets.

Much important information has been obtained by this means, but the method has serious disadvantages. The chamber is only sensitive for a short time after each expansion, so that many exposures often have to be made before a given event can be observed, or the equipment must be linked to a " counter " which triggers its operation.* A Wilson cloud chamber with its ancillary equipment is necessarily rather bulky and heavy. The most serious defect, however, has been the difficulty of studying a complete process (particularly in the case of meson reactions) because the range of the particles was many times the diameter of the chamber.

It has, however, long been known that photographic emulsions can record the tracks of the more heavily-ionizing particles (such as alpha particles), and special photographic materials have now been evolved which are practically as sensitive as the cloud chamber.(17) These emulsions have a very uniform grain size, a high silver-halide/gelatin ratio, and a remarkably low proportion of " fog " grains. The most sensitive will record all known ionizing particles, and they can all be coated at thicknesses up to $\frac{1}{25}$ in. (1,000 μ), and have about two thousand times the " stopping power " of air. This means that the linear dimensions of the tracks are greatly reduced, so that an alpha particle having a range of 1·6 in. (40 mm.) in air will only travel 0·0008 in. (20 μ) in a nuclear-track emulsion. The images recorded by such emulsions are thus *microphotographic* in comparison with cloud-chamber photographs, and also merit this description since they must be viewed with a microscope.

This method of observing nuclear reactions has several important advantages. The chance of observing rare events is greatly increased by the fact that the emulsion is continuously sensitive, and by its enormous relative volume. Thus a 3 × 1 in. (75 × 25 mm.) plate coated with a 0·016-in. (400-μ) thick emulsion corresponds to an air space of dimensions 500 × 166 × 2·6 ft. (150 × 50 × 0·8 metres), or a hundred thousand times the volume of a large cloud chamber. This large effective volume has been of particular value for investigating meson reactions, since it increases the probability of observing the complete life history of these short-lived and elusive particles. Thus many cases have now been recorded in which the track of a cosmic-ray particle has been seen to enter an emulsion and cause the disintegration of one of its constituent atoms with the emission of one or more mesons. One of the meson tracks can then be followed several hundreds of microns through the emulsion, until the particle decays and triggers off another disintegration. These valuable properties of nuclear-particle emulsions are combined with great portability, which makes it possible for them to be carried up to altitudes of 100,000 ft. in balloons, or to 100 miles or more in rockets. At such altitudes cosmic-ray particles have been detected, which have never been observed at sea-level, and the results obtained by such flights have been of great importance to cosmic-ray research. The value placed on this work can be judged from the fact that a Nobel Prize for Physics was awarded to Professor Powell of Bristol for his development and use of this technique.

* Continuously-sensitive " diffusion " cloud chambers are now being developed.

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APPENDIX I

Processing Formulae

The formulae given in the following pages are those which the author has found particularly useful for the production of extreme-resolution images on concentrated-Lippmann emulsions, and for the making of intermediate transparencies. American readers should note that some of the formulae published by Kodak Ltd. in Great Britain are not included in the lists printed by the Eastman Kodak Company, but equivalent figures in American units are included for their convenience. These recommendations are necessarily based on experience with sensitive materials commercially available in Great Britain. It is not likely that they will be found unsuitable for plates manufactured in other countries, but if in doubt the reader should use the formulae recommended by the manufacturer of the material he is using. In the American versions 28% acetic acid has been substitued for the " glacial ", and " desiccated " sulphite and carbonate should be used where " anhydrous " is given.

(A) Developers

High-contrast Negative Developer. " Kodak " Formula D.19b

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
" Elon " *	77 grains	2·2 grams	32 grains
Sodium sulphite (anhyd.) .	5 ounces 330 grains	72·0 grams	2 ounces 180 grains
Hydroquinone	310 grains	8·8 grams	125 grains
Sodium carbonate (anhyd.)	3 ounces 370 grains	48·0 grams	1 ounce 260 grains
Potassium bromide . . .	140 grains	4·0 grams	58 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

* Monomethyl paraminophenol sulphate, also known as " Metol ", " Genol ", etc.

When used at full strength, this developer is useful for obtaining high contrast on photomechanical or high-speed negative materials, without the use of caustic solutions. May be used for developing master negatives with development times up to 10 minutes at 20° C. (68° F.).

Physical Developer

(Formula due to Lüppo-Cramer. *Photographische Industrie* (1921), page 797)

STOCK SOLUTION A

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
" Elon "	175 grains	20 grams	290 grains
Citric acid	350 grains	40 grams	1 ounce 150 grains
Gum arabic (20% solution)	380 minims	40 c.c.	1¼ ounces
Distilled water to make	20 ounces	1,000 c.c.	32 ounces

STOCK SOLUTION B

Silver nitrate. 10 per cent. solution in distilled water

Solution A should be kept for only about one week after making up.

Solution B will keep indefinitely in a brown bottle.

As with other physical developers, all vessels should be cleaned before use, preferably with concentrated nitric acid. (*Caution*—very corrosive !)

For use, add 1 part of Solution B to 25 parts of A *just* before starting development, and develop for up to 5 minutes at 20° C. (68° F.). This developer may be used for developing latent images in various emulsions (Lippmann, wet-collodion, silver-albumen, mercury-diazo), and also for intensifying chemically developed images in Lippmann or concentrated-Lippmann emulsions.

High-contrast Developer for Concentrated-Lippmann Emulsions. " *Kodak* " *Formula D.*178

STOCK SOLUTION

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Sodium sulphite (anhyd.)	7 ounces 90 grains	90 grams	3 ounces
Hydroquinone	3 ounces 265 grains	45 grams	1½ ounces
Sodium hydroxide (caustic soda)	1 ounce 190 grains	18 grams	260 grains
Potassium bromide	2 ounces 175 grains	30 grams	1 ounce
Water to make	80 ounces	1,000 c.c.	32 ounces

Note. The hydroquinone will not dissolve completely until the sodium hydroxide is added.

Use 2 parts Stock Solution to 1 part of water, and develop Maximum Resolution plates for 3–4 minutes at 20° C. (68° F.). This solution can also be used for high-contrast development of photomechanical materials, when making line negatives. It gives appreciably higher contrast than " Kodak " Formula D.19*b*. For this latter purpose it is better to increase the sodium hydroxide content to 3 ounces (British), 37·5 grams (Metric) or 1¼ ounces (American). This gives " Kodak " Formula D.8.

Normal-contrast Developer for Photomechanical or Concentrated-Lippmann Emulsions. " *Kodak* " *Formula D.*158

STOCK SOLUTION

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
" Elon "	110 grains	3·2 grams	47 grains
Sodium sulphite (anhyd.)	4 ounces	50·0 grams	1 ounce 280 grains
Hydroquinone	1 ounce 40 grains	13·3 grams	195 grains
Sodium carbonate (anhyd.)	5 ounces 220 grains	69·0 grams	2 ounces 130 grains
Potassium bromide	32 grains	0·9 gram	13 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

For use, dilute with an equal volume of water, and develop for up to 4 minutes at 20° C. (68° F.). This developer is recommended for Maximum-Resolution plates in applications where preservation of fine-grain structure is more important than high contrast, e.g. for microradiography.

Low-contrast Developer for making Transparencies. " *Kodak* " *Formula D.*165

STOCK SOLUTION

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
" Elon "	210 grains	6 grams	90 grains
Sodium sulphite (anhyd.)	2 ounces	25 grams	365 grains
Sodium carbonate (anhyd.)	3 ounces	37 grams	1 ounce 100 grains
Potassium bromide	35 grains	1 gram	15 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

Dilute 1 part of Stock Solution with 3 parts of water, and develop for up to 4 minutes at 20° C. (68° F.). When used with photogravure plates, this developer can be used to make continuous-tone transparencies with a low density range, for use with extreme-resolution emulsions having high contrast and a short exposure scale.

Reversal Processing for Concentrated-Lippmann Emulsions. " *Kodak* " *Formula R.*21

STOCK SOLUTION A. BLEACHING BATH

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water	80 ounces	1,000 c.c.	32 ounces
Potassium dichromate	4 ounces	50 grams	1½ ounces
Sulphuric acid (concentrated)	4 fluid ounces	50 c.c.	1½ fluid ounces

Dissolve the dichromate in the water, then add the sulphuric acid slowly, with constant stirring, to the cold solution. For use dilute one part of Stock Solution with nine parts of water.

STOCK SOLUTION B. CLEARING BATH

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water	80 ounces	1,000 c.c.	32 ounces
Sodium sulphite (anhyd.) .	4 ounces	50 grams	1½ ounces
Sodium hydroxide (caustic soda)	35 grains	1 gram	15 grains

Reversal Process

Develop 3 minutes in D.178 (see Appendix I, A),
Wash 2 minutes in running water,
Bleach in R.21A (diluted 1 + 9) for about 45 seconds,
Turn on room lights,
Clear for 30 seconds in undiluted R.21B,
Wash in running water for 2 minutes,
Expose for 15 seconds close to a 100-watt bulb,
Re-develop in D.178 for 3 minutes at 68° F.,
Wash for 5 minutes, and bathe 2 minutes in clean industrial spirit to remove sensitizing dye.

Prevention of Lime Scum in Developers

If developer solutions cannot be conveniently compounded with distilled or soft water, scum due to precipitation of lime and magnesium salts in the developer may be prevented in two ways :

(*a*) The complete solution diluted to working strength may be left for the precipitate to settle. After several hours the clear supernatent liquor can be decanted and used.

(*b*) Scum formation can be inhibited by adding sequestering agents such as "calgon" (sodium hexametaphosphate) to the developer. One source (1) suggests addition of from 1 to 5 grams per litre (35 to 175 grains per 80 ounces), and another (2) recommends 0·5 gram per litre for developers containing borax, and 2 grams per litre for developers containing carbonate.

References

(1) Data booklet GN.5 (page 16). (Published by Kodak Ltd., England.)
(2) Clerc, L. P. *Photography. Theory and Practice* (3rd Edition). Pitman (London), 1954, page 197.

(B) Stop Baths

Non-Hardening Stop Bath. "Kodak" Formula SB. 1a

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water	80 ounces	1,000 c.c.	32 ounces
Acetic acid (glacial)	4 ounces	50 c.c.	—
or Acetic acid (28% solution) .	—	125 c.c.	4 ounces

A short immersion of concentrated-Lippmann emulsions, after development in a caustic-hydroquinone developer, greatly reduces the risk of stain.

Tropical Hardening Stop Bath. "Kodak" Formula SB.4

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water	80 ounces	1,000 c.c.	32 ounces
Potassium Chrome alum . .	2 ounces 175 grains	30 grams	1 ounce
Sodium sulphate (cryst.) . .	11 ounces 90 grains	140 grams	—
or Sodium sulphate (anhyd.) .	4 ounces 350 grains	60 grams	2 ounces

The freshly-made bath is a violet-blue colour and keeps indefinitely while unused. It is unwise to store a partially-used bath, and the solution should in any case be discarded after the equivalent of twenty 10 × 8 in. plates per gallon have been treated.

Agitate the plates for 30–45 seconds to avoid unevenness when they are first transferred from the developer, and leave them for 3 minutes. The use of this solution counteracts the tendency of the emulsion to swell very rapidly when rinsing after development. Its use is likely to prove beneficial when exact preservation of image size is required.

(C) Fixing Bath

Acid Hardener Stock Solution. "Kodak" Formula F.53

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Sodium sulphite (anhyd.)	4 ounces	50 grams	1 ounce 300 grains
Acetic acid (glacial)	6 ounces	75 c.c.	—
or Acetic acid (28% solution) . .	—	270 c.c.	8½ ounces
Potassium alum	8 ounces	100 grams	3 ounces 150 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

Dissolve the sulphite in one quarter of the final volume of warm water (about 52° C. or 125° F.). Allow to cool, and add the acetic acid slowly and with constant stirring. Dissolve the potassium alum in one half of the final volume of *hot* water, and allow to cool below 21° C. (70° F.), before adding this to the sulphite-acetic mixture and making up to volume.

Acid Hardening-fixing Bath for Plates. "Kodak" Formula F.54a

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Warm water (52° C., 125° F.) .	40 ounces	500 c.c.	16 ounces
Sodium thiosulphate (hypo. cryst.)	32 ounces	400 grams	13 ounces 160 grains
To this when cold add :			
"Kodak" Liquid Hardener . .	6 ounces	75 c.c.	2½ ounces
or :			
F.53 Stock Solution	15 ounces	185 c.c.	6 ounces
Water to make	80 ounces	1,000 c.c.	32 ounces

This bath will fix most plate emulsions in a few minutes, but ten minutes' treatment at 20° C. (68° F.), is recommended to ensure satisfactory hardening of gelatin emulsions. Prolonged immersion of fine-grain silver images is to be avoided, since it is likely to result in a reduction of density.

(D) Miscellaneous Formulae

Ammonium-thiosulphate Reducer and Stain Remover

(R. W. Henn, J. I. Crabtree and H. D. Russell.
J. Phot. Soc. Am. (*Phot. Sci. and Tech.*), **17B,** 1951, 110)

Stock Hardener Solution. " Kodak " Formula F.5a

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water (52° C., 125° F.) .	50 ounces	625 c.c.	21 ounces
Sodium sulphite (anhyd.) .	6 ounces 110 grains	75 grams	2 ounces 220 grains
Acetic acid (glacial) . .	5 ounces 120 minims	66 c.c.	—
or Acetic acid (28% solution)	—	236 c.c.	9 ounces
Boric acid (cryst.) . . .	3 ounces 55 grains	37·5 grams	1 ounce 110 grains
Potassium alum . . .	6 ounces 110 grains	75 grams	2 ounces 220 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

To prepare reducer mix together :

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Ammonium thiosulphate .	3 ounces	150 grams	5 ounces
F.5*a* Stock Solution .	4 ounces	200 c.c.	6½ ounces
Citric acid (for slow-working solution)	130 grains	15 grams	½ ounce
Citric acid (for fast-working solution)	260 grains	30 grams	1 ounce
Water to make	20 ounces	1,000 c.c.	32 ounces

The authors describe the use of these solutions for selectively removing stain with a minimum of attack on the chemically-developed image. When used with microphotographic images the necessary time of treatment (up to 20 minutes at 20° C. ; 68° F.), should be found by preliminary tests ; or the treatment should be interrupted at intervals to permit its progress to be assessed.

Farmer's " Cutting " Reducer. " Kodak " Formula R.4a

STOCK SOLUTION A

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Potassium ferricyanide . . .	6 ounces	75 grams	2½ ounces
Water to make	80 ounces	1,000 c.c.	32 ounces

STOCK SOLUTION B

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Sodium thiosulphate (hypo. cryst.)	19 ounces	240 grams	8 ounces
Water to make	80 ounces	1,000 c.c.	32 ounces

For use, take 1 part of Solution A, 4 parts of Solution B and add 27 parts of water. Pour the mixed solution at once over the negative to be reduced. Watch closely, and remove the negative as soon as sufficient reduction has occurred. Wash thoroughly before drying. This solution is suitable for making line " master " negatives on " process " plates, but is likely to prove too drastic for truly microscopic images. (See appropriate sections of Chapter 4.)

Mercury Intensifier. " Kodak " Formula IN.1

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Potassium bromide	1 ounce 350 grains	22·5 grams	¾ ounce
Mercuric chloride	1 ounce 350 grains	22·5 grams	¾ ounce
Water to make	80 ounces	1,000 c.c.	32 ounces

Bleach the developed image in the above solution until it is white, and wash thoroughly. Blacken in a developer such as D.19*b* or D.154 (see Appendix I, A). The process can be repeated.

The same intensifier is useful for increasing the density and contrast of " line " negatives, particularly if they have first been treated in a " cutting " reducer. For this application it is often more convenient to blacken in the following solution :

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Sodium or potassium cyanide * .	1 ounce 90 grains	15·0 grams	½ ounce
Silver nitrate	1 ounce 350 grains	22·5 grams	¾ ounce
Distilled water	80 ounces	1,000 c.c.	32 ounces

* *Warning.* Cyanide is a *deadly poison* and should be handled with extreme care. If allowed to mix with acid solutions it will evolve a deadly gas. When discarding cyanide solutions, first run the cold tap for at least 15 seconds, pour the solution slowly down the drain, and flush out the sink. Never use cyanide solutions in poorly ventilated rooms.

Dissolve the cyanide and silver nitrate separately each in half of the water, and add the silver nitrate to the cyanide until a permanent precipitate is *just* formed. Allow the mixture to stand for some time and filter.

Etch-bleach Bath. " Kodak " Formula EB.2

STOCK SOLUTION A

	Avoirdupois (British)	*Metric*	*Avoirdupois (American)*
Water (52° C., 125° F.) .	60 ounces	750 c.c.	24 ounces
Copper sulphate (cryst.) .	9 ounces 220 grains	120 grams	4 ounces
Citric acid	12 ounces	150 grams	5 ounces
Potassium bromide . . .	260 grains	7·5 grams	110 grains
Water to make	80 ounces	1,000 c.c.	32 ounces

SOLUTION B

Hydrogen peroxide 3 per cent. solution.
(" 10 volume " solution, as purchased.)

For use, mix equal parts of A and B Solutions. The bleaching of the silver image should be accompanied by rapid disintegration of the gelatin in the blackened areas. Hydrogen peroxide solutions tend to decompose on storage. If the peroxide is too weak, the proportion of Solution B may be increased. The bleaching action will then be somewhat slower, but the final result should be quite satisfactory.

APPENDIX II

Lens Calculations

(A) Approximate Relationship between u and v

When focusing an objective for microphotography it is often useful to know the mutual relationship between changes in the distance of the object plane (u), and the corresponding changes in the objective-image distance (v).

Changes in one quantity resulting from a change in the other can be calculated exactly from the lens formula (Chapter 5, page 80), but it is usually only necessary to know the approximate magnitude of these quantities. Values sufficiently accurate for most practical purposes can be found from Table VII, which has been computed for objectives of nominal focal length.

TABLE VII

Changes in v (Objective-image Distance) produced by Changes in u (Distance of Object Plane)

Change in u	*Corresponding changes in v for focal length value of*						
	4 *mm.*	8 *mm.*	12·5 *mm.*	16 *mm.*	25 *mm.*	50 *mm.*	100 *mm.*
mm.							
∞–10,000	0·0016	0·006	0·016	0·026	0·063	0·251	1·010
10,000– 5,000	0·0016	0·007	0·015	0·025	0·063	0·254	1·031
5,000– 2,000	0·0048	0·019	0·048	0·078	0·191	0·777	3·222
2,000– 1,000	0·0081	0·033	0·079	0·131	0·324	1·350	5·848
1,000– 900	0·0018	0·007	0·018	0·030	0·073	0·309	1·389
900– 800	0·0022	0·009	0·022	0·037	0·093	0·392	1·786
800– 700	0·0029	0·011	0·029	0·047	0·119	0·513	2·381
700– 600	0·0039	0·016	0·039	0·064	0·161	0·699	3·333
600– 500	0·0054	0·022	0·054	0·091	0·229	1·011	5·000
500– 400	0·0081	0·033	0·083	0·138	0·351	1·587	8·333
400– 300	0·0137	0·056	0·141	0·234	0·606	2·857	16·667
300– 200	0·0275	0·114	0·289	0·490	1·298	6·667	50·0

To Use the Table

All the distances in the table are given in millimetres, and can be converted to inches by using the factor 0·001 in. equals 0·025 mm. (to be exact 0·0254 mm.). It should be remembered that all the changes are of opposite sign. Thus a *decrease* in u is accompanied by an *increase* in v, and conversely.

Figures for larger changes than those tabulated can be calculated by adding the changes in the vertical columns, and approximate values for smaller changes can be found by dividing the appropriate figures by the factor needed. In practice this table is likely to be used in two ways.

(i) In the focusing of distance pieces (see page 121) it is necessary to know by how much the distance piece should be shortened (i.e. decrease in v), to move the object plane out by a required amount. For instance, with a 16-mm. objective a movement of the object plane from 700 to 800 mm. should result from shortening the distance piece by 0·047 mm. Similarly a movement from 500 to 800 mm. would need the removal of 0·091 plus 0·064 plus 0·047 mm. or 0·202 mm. in all.

(ii) This table can also be used to show the magnitude of the changes in the distance (u) needed to produce small changes in v; for instance, when fine focusing is performed by changing the camera-to-object-plane distance. Thus with a 4-mm. objective a decrease of u from 700 to 600 mm. will increase the objective-image distance (v) by 0·0039 mm.

(B) Precise Relationship between *u* and *v*

When the figures given in Table VII are not sufficiently precise, it is necessary to make allowance for the difference between the actual and the nominal focal lengths of the objective. This can be simply done by tabulating related values of u and v for an objective whose focal length is unity. As shown in Chapter 5 (page 81), this simplifies their relationship to the form

$$v = \frac{u}{u-1}$$

Moreover, the degree of reduction is found by dividing u by v, hence

$$R = \frac{u}{v} = \frac{u}{\dfrac{u}{u-1}} = u - 1$$

A useful table can be constructed by tabulating a suitable range of reductions, and related values of u, from which v is simply calculated.

TABLE VIII

Relation between u and v for a Focal Length of Unity

Degree of reduction	*u*	*v*	*Degree of reduction*	*u*	*v*
10	11	1·1000	56	57	1·0179
12	13	1·0833	68	69	1·0147
14	15	1·0714	80	81	1·0125
17	18	1·0588	96	97	1·0104
20	21	1·0500	112	113	1·0089
24	25	1·0417	136	137	1·0074
28	29	1·0357	160	161	1·0063
34	35	1·0294	192	193	1·0052
40	41	1·0250	224	225	1·0045
48	49	1·0208			

Figures for u and v for any given objective can then be found by multiplying the values in this table by the actual focal length of the objective. The precision obtained is likely to be limited by the accuracy with which the focal length can be measured.

If many calculations of this type have to be made with varying degrees of reduction, it is convenient to plot u against v on single logarithmic paper. v is plotted on the linear scale and u on the logarithmic scale. Now if R is the required reduction, R plus 1 is the value of u; and with the aid of this graph the value of v corresponding to R plus 1 is read off. The result can be checked by dividing u by v, which should equal R within about 0·1 per cent. Since this method provides values for both u and v, the object-plane-to-image-plane distance D, which equals their sum, is also directly obtainable. This is convenient, since the distance D can be measured more easily and accurately than either u or v separately.

(C) Depth of Field and Depth of Focus

It is apparent from Chapters 9 and 10 that sharp images can be obtained in some cases at different levels in a microphotographic emulsion. In fact, the depth of focus is not determined only by the performance of the objective, but is also influenced by the thickness and transparency of the emulsion.

With concentrated-Lippmann emulsions, in particular, the phenomenon of optical sectioning permits sharp images of fine black lines to be obtained at all levels in the emulsion. In fact, the thickness of the emulsion effectively supplements the depth of focus and necessarily also the depth of field. The depth of field which should for this reason be obtained under different conditions with an emulsion layer 5 μ thick is shown in the following table.

TABLE IX

Depth of Field equivalent to 5 μ Depth of Focus (Approximate Thickness of Commercial Concentrated-Lippmann Emulsion)

Distance of object plane (millimetres)	*Depth of field (in millimetres) equivalent to 5 μ depth of focus for objectives of focal length*						
	4 *mm.*	8 *mm.*	12·5 *mm.*	16 *mm.*	25 *mm.*	50 *mm.*	100 *mm.*
200	12	2·88	1·13	0·66	0·25	0·045	0·005
300	*27·4*	6·7	2·65	1·58	0·61	0·100	0·020
400	*49*	12	4·8	2·88	1·13	0·25	0·045
500	*77*	19	7·6	4·58	1·81	0·41	0·080
600	*111*	27·4	11·0	6·67	2·65	0·61	0·100
700	—	*37·4*	15·1	9·14	3·65	0·85	0·18
800	—	*49*	19·9	12·0	4·81	1·13	0·25
900	—	*62*	25·2	15·3	6·13	1·45	0·32
1,000	—	*77*	31·2	18·9	7·62	1·81	0·41
2,000	—	*310*	*126*	77	31·2	7·61	1·81
5,000	—	—	—	*485*	198	49	12
10,000	—	—	—	—	—	198	49

These figures form a useful basis for deciding the magnitude of the changes in *u* which should be made in different conditions, when focusing by changing the camera-object-plane distance.

In interpreting this table it should be noted that these figures were calculated from a formula which is only accurate when the changes in object distance are relatively small.

The figures in *italics* should, therefore, be considered as approximate, since the changes exceed 5 per cent. of the total distance.

APPENDIX III

Series of Exposure Times

The response of the human eye, or the density produced by a silver-halide emulsion, are approximately proportional to the logarithm of the light intensity falling on them ; and for this reason it is generally recommended that photographic exposure-tests should be made with a geometrical series of intensities or times. This results in the production of images showing approximately equal density increases with each increase of exposure, and also having equal increases of visual blackness. Other advantages of geometrical series are that they are consistent with the system used for marking lens diaphragms, and permit any desired accuracy to be obtained over a given exposure range with a minimum number of tests.

An important factor in designing exposure tests is the magnitude of the increment by which the exposures are increased. This depends firstly on how nearly the correct exposure is already known, and secondly on how closely the exposure must be controlled to give the photographic quality required.

If the conditions are completely unfamiliar, time can often be saved by making a test with a large factor such as 4 or 10. With the factor 4, a range of 1,000 : 1 can be covered with only 6 test exposures (i.e. 1, 4, 16, 64, 256 and 1,012 seconds), and if the correct exposure falls within the range of times given, one or other of the images will be incorrectly exposed by a factor of not more than 2. A second test with a total range of 2 : 1 will then enable the correct exposure to be determined precisely.

Photographers making contact prints or enlargements are often advised to make exposure tests using a factor of 2 (i.e. using times such as 5, 10, 20, 40 . . . seconds), but this factor is too large to secure the highest possible print quality with fixed development conditions. In practice the prints are often inspected during development, which is curtailed or prolonged to compensate for a slightly incorrect exposure. The disadvantage of such a large factor really becomes apparent when making prints from small-density-range negatives on high-contrast papers, or when making microphotographs on high-contrast emulsions. In the latter instance particularly, the problem is aggravated by the impracticability of developing by inspection.

A more sensitive control is obtained by using exposure times selected from the series :

10, 14, 20, 28, 40, 56, 80 . . . seconds

Each time is approximately $\sqrt{2}$ greater than the preceding one and the factor by which the exposure increases is equivalent to half a " stop ". When the lamp intensity and development conditions are carefully controlled, it is sometimes useful to use an even finer series :

10, 12, 14, 17, 20, 24, 28, 34, 40, 48, 56, 68, 80 . . . seconds

The factor is approximately $\sqrt[4]{2}$, corresponding to a quarter of a stop.

When making exposure tests for microphotography, the surest practice is to expose a complete image at each exposure time. With this method and exposure times of ten seconds or longer, manual timing with the aid of a large-dial darkroom clock is sufficiently accurate even for the very fine $\sqrt[4]{2}$ series of times.

If these fine exposure series are used when enlarging, the $\sqrt{2}$ series may be built up by covering successive strips of one sheet of paper as each exposure time elapses. Thus the whole sheet could be exposed for 10 seconds, and further times of 4, 6, 8, 12, 16 and 24 seconds given with an opaque card moved farther over the paper between each exposure. Thus neighbouring strips of the emulsion are exposed respectively for 10, 14, 20, 28, 40, 56 and 80 seconds. With the finest ($\sqrt[4]{2}$) series, however, errors in the timing of the increments, or in the response of the emulsion to intermittent exposures, may make this cumulative-exposure technique unsatisfactory. The test should, therefore, preferably be made with separate strips of paper, each exposed for a single time from this series.

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